U.S. DEPARTMENT OF COMMERCE
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AD-A028 315

REXOR ROTORCRAFT SIMULATION MODEL

VOLUME II. COMPUTER IMPLEMENTATION

LOCKHEED-CALIFORNIA COMPANY

PREPARED FOR
ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY

JULY 1976

232110

USAAMRDL-TR-76-23B

ADA028315

REXOR ROTORCRAFT SIMULATION MODEL

Volume II - Computer Implementation

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July 1976

Final Technical Report

Approved for public release; distribution unlimited.

Prepared for

U. S. Army Aviation Systems Command
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St. Louis, Mo. 63166

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Fort Eustis, Va. 23604

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: USAAMRDL-TR-76-28B	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): REXOR ROTORCRAFT SIMULATION MODEL - Volume II, Computer Implementation	5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report
	6. PERFORMING ORG. REPORT NUMBER: LR 27463
7. AUTHOR(s): W.D. Anderson, F. Conner, P. Kretsinger, J.S. Reaser	8. CONTRACT OR GRANT NUMBER(s): DAAE11-66-C-3667(H)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Lockheed California Company, PO Box 551, Burbank, Calif. 91520	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Aviation Systems Command, P.O. Box 209, St. Louis, Missouri 63166	12. REPORT DATE: July 1976
	13. NUMBER OF PAGES: 100
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Eustis Directorate, U.S. Army Air Mobility R&D Laboratory, Fort Eustis, Virginia 23604	15. SECURITY CLASS (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Volume II of three volumes.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aerodynamics
Airfoil Tables
Rotors
Computer Programs
Digital Computers
Rotorcraft Simulation
Helicopters
Nonlinear Models
Blade Dynamics
Inplane Damping
Matrix Representation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a rotorcraft nonlinear simulation called REXOR, and is divided into three volumes. The first volume is a development of rotorcraft mechanics and aerodynamics. The second is a development and explanation of the computer code required to implement the equations of motion. The third volume is a user's manual, and contains a description of code input/output as well as operating instructions.

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The REXOR math model has been written for a single four-bladed, gyro-controlled, hingeless-rotor helicopter with additional capability for analysis of teeter or hinge-offset rotor systems with conventional controls and two or four blades. The helicopter modeled may be conventional in design, winged or compounded. Modeling emphasis is on an accurate main rotor description with additional degrees of freedom to describe the rest of the helicopter.

REXOR has been implemented on IBM 360 and CDC 6000 series equipment. The operating instructions are primarily based on the 360 equipment useage with additional instructions to show use on the 6000 series equipment.

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1. PACKAGE ORGANIZATION

1.1 FLOW CHART

The operation of REXOR in the broadest sense consists of first establishing an equilibrium set of initial conditions followed by a time history sequence determined by control inputs and the equations of motion. The first part of the operation is called TRIM and the second part is termed FLY.

The program operations REXOR computes in TRIM are given in Figure 1-1. The FLY operations are shown in Figure 1-2. The computation blocks are briefly annotated for completeness in these figures, and are developed more fully in the following subsections. Likewise the available options are explained below.

1.2 OPERATION MODES

1.2.1 TRIM

Referring to Figure 1-1, the first major operation performed in REXOR is for the executive routine MAIN to call the subroutine TRIM. As programmed, TRIM can process the equations of motion of the main rotor ensemble and fuselage accelerations. The main rotor trim configuration is the same as will be used in FLY, that is, a complete rotor and control system. The code in TRIM contains the equations for other options. However, these are not fully developed or sufficiently reliable to be considered as operational.

The subroutines LOADS, SWEEP, ACCEL and associated subroutines are called from TRIM. These subroutines form the generalized mass and force matrices as developed in Volume I, Section 6 for the rotor and control system. The correcting acceleration, Section 6.3, is formed by the subroutine MIC26. The predictor numerical integration is done in the subroutine INTG with the entry points of PRED and CORECT.

The subroutine TRIM uses the newly updated set of accelerations to adjust the selected control set to converge on the desired initial condition set. The initial condition set can specify unaccelerated flight or an initial load factor in a coordinated turn. The control set selection available is given in Volume III. The trim error acceleration set (determined by the control set selected) operates the control set through input gain factors to null the errors. Trim is detected by simultaneous steadiness of all the selected trim controls. The exit from TRIM is to MAIN which in turn transfers control directly to FLY. A control flag to save the completed trim data is available and operates prior to the transfer to MAIN and FLY. The feature saves the convergence time when running the same case at a later date.

1.2.2 FLY

As shown in Figure 1-2, the operation of FLY closely resembles that of TRIM; namely the equations of motion are still formed by the subroutines LOADS, SWEEP, ACCEL and associated routines. The difference is that the entire set of equations are being computed and that the controls are driven by commands rather than trim error balance sources.

The control system can operate with a number of different configurations. A hard swashplate and flexible swashplate - external control gyro configurations are computed directly in the subroutine FLY. For the isolated internal gyro system (Lockheed Advanced Mechanical Control System) the subroutine IGYRO is used. This subroutine in turn uses the subroutine BIRD1 (with multiple entry points) to form and solve the equations of motion of this system apart from the main flow of computation. The shaft bending equations are also integrated by this branch computation.

The input commands for cyclic, collective and pedals come from the subroutine CNTROL (entry point PICNTL). This gives a time history input position and rate commands from the input data set (Volume III). A number of flight profile follower - autopilots exist in the code, and can be used at this point. However, the code is not considered to be documented or operational.

The available airfoil data schemes are shown in Figure 1-2. For clarity the less involved 7 table lookup is shown in the computation loop. The fast aero lookup system is shown as an alternate at the bottom of the figure together with the dynamic stall option (subroutine STALL) which may be used with this lookup procedure. The background material for the lookup routines is contained in Volume I, Section 7 and Section 4 of this Volume.

Other options which are activated from the subroutine fly are variable rotor speed (subroutine ETORQ), quasi-static blade torsion (subroutine TORS1 entry TORS), and isolated pitch horn bending (subroutine PHORN).

Operation of the subroutine FLY continues in a loop fashion until the allowed maneuver time limit (input) or unrealistic loads are detected due to true rotorcraft problems or computation numerical difficulties. Exit from FLY returns control to MAIN. Here, either a new case or an execution termination occurs depending on the input data.

1.3 ROUTINES IN PACKAGE

In this section the computer routines which comprise REXOR are explained in sufficient detail to allow the reader to identify and map out the computation procedures explained in Volume I. The REXOR routines are summarized in Table 1-1. The following subheadings treat the routines as listed in this table. The subroutines ACCEL, LOADS and SWEEP form the nucleus of the

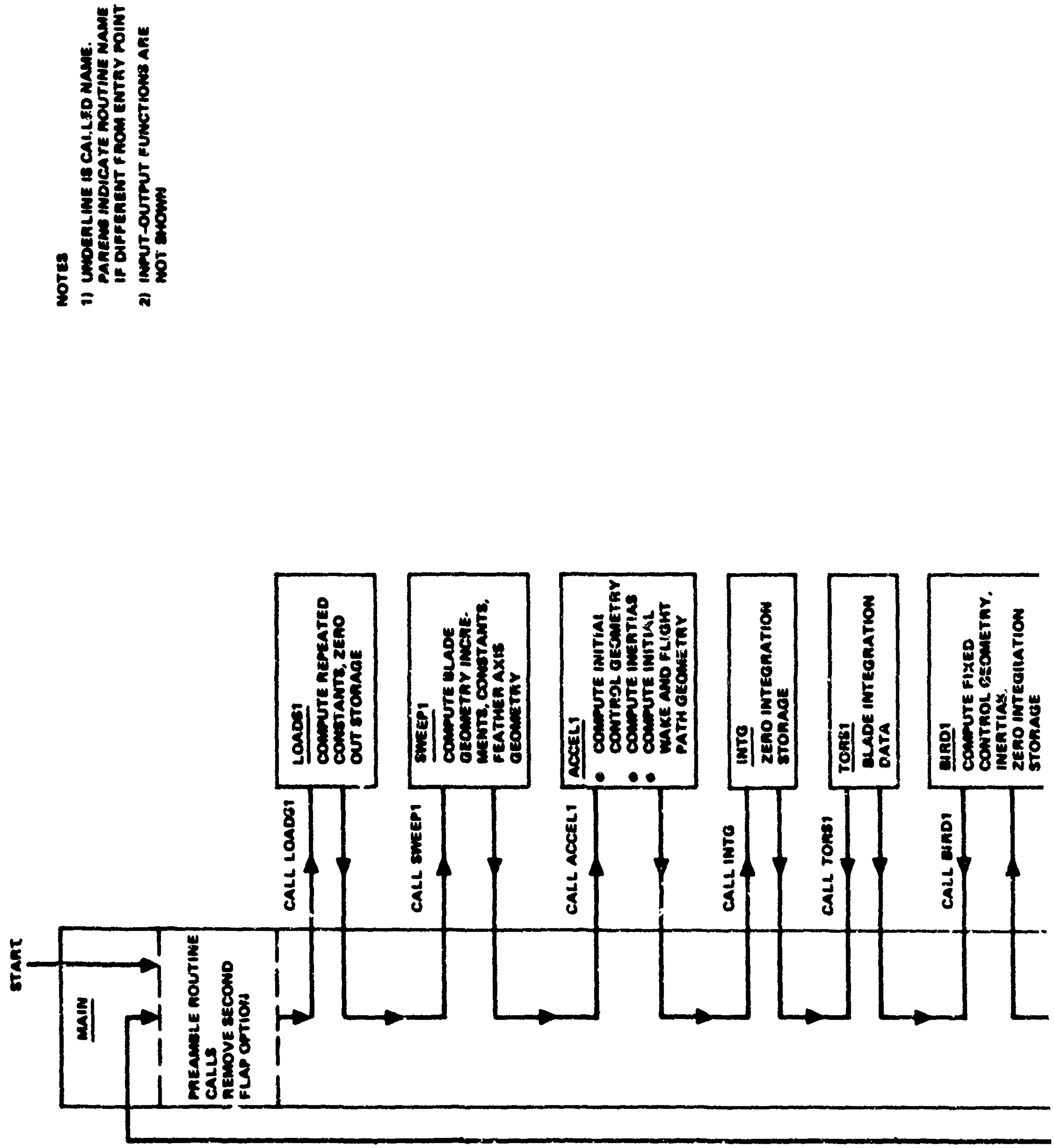
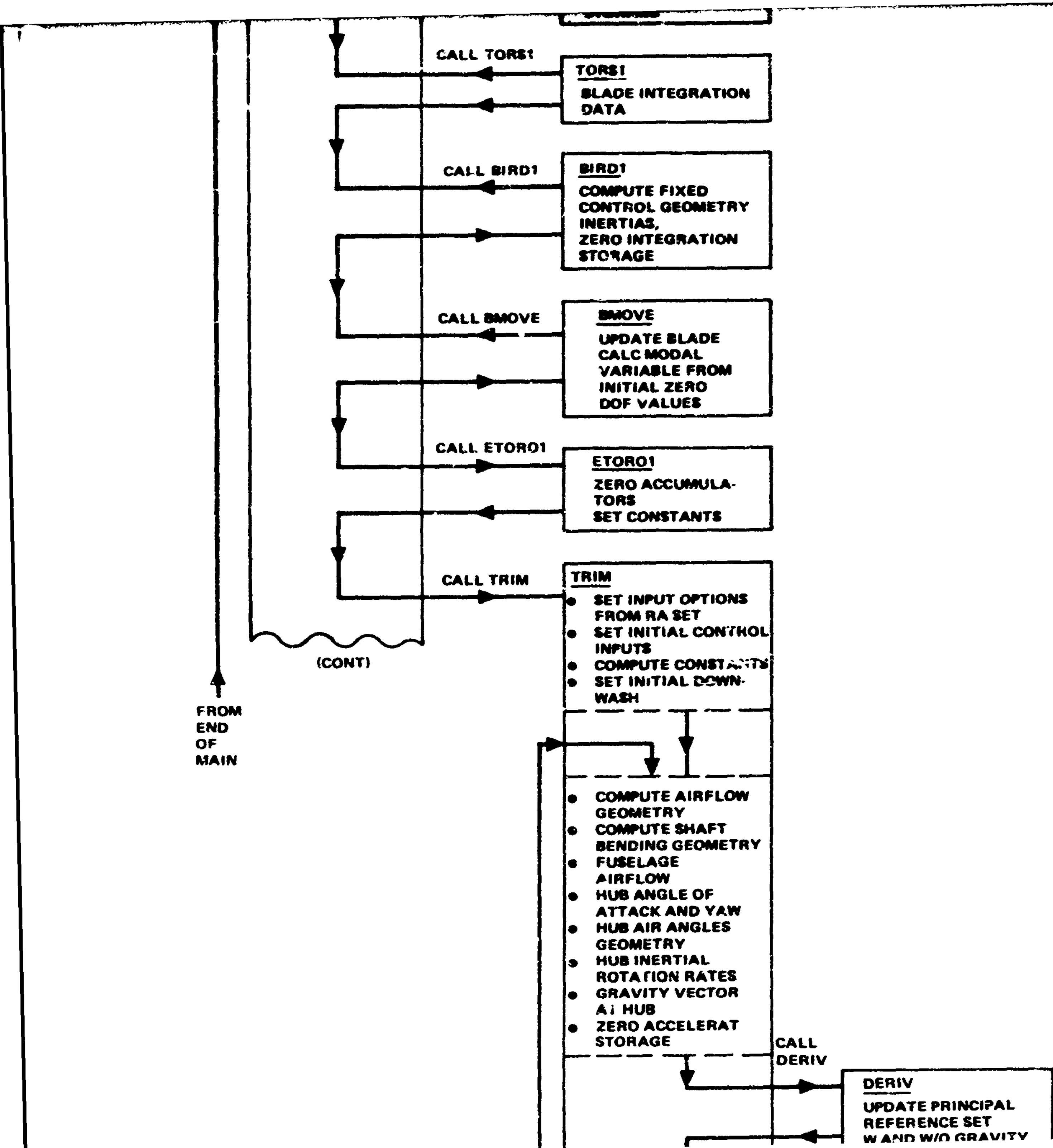
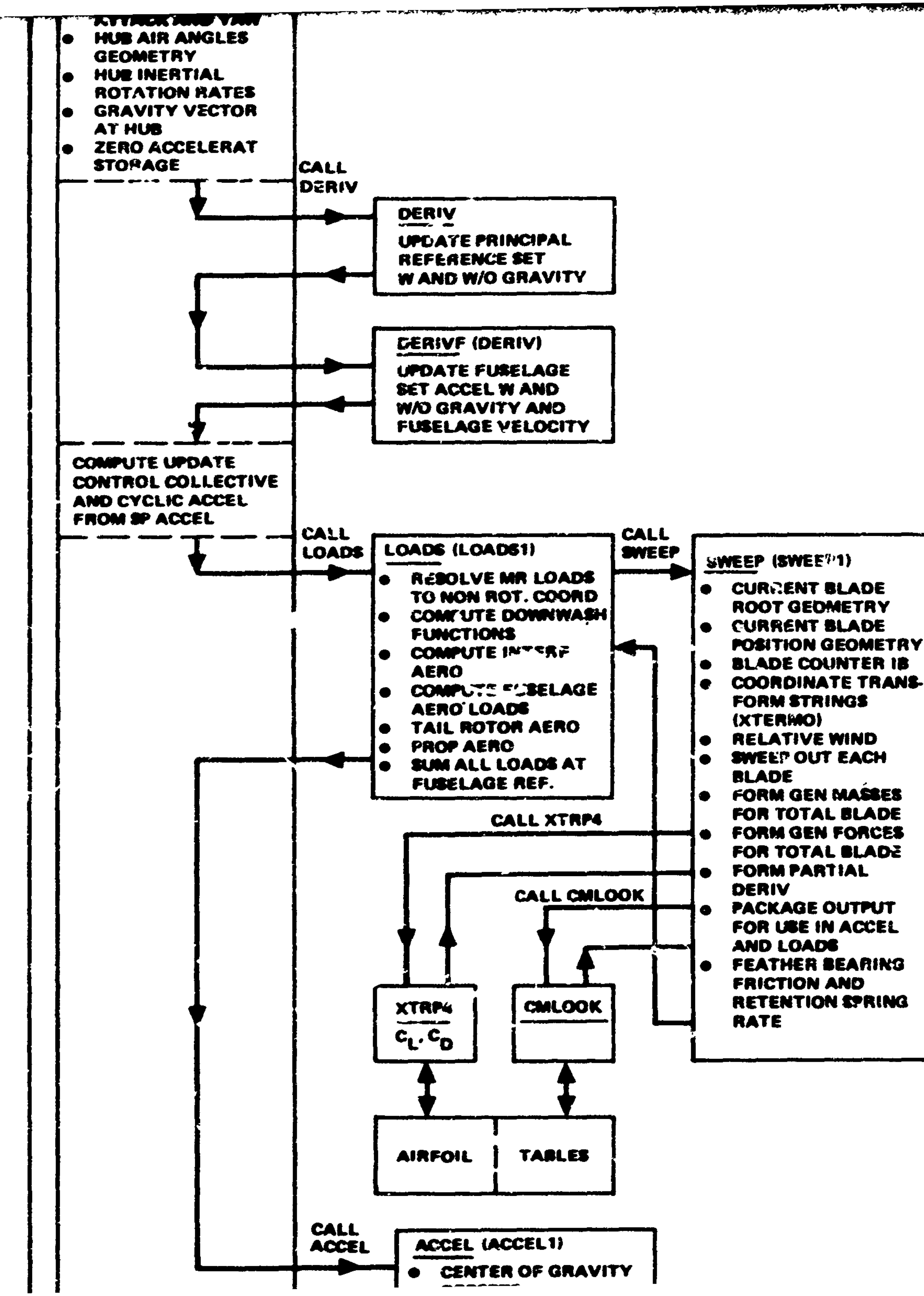


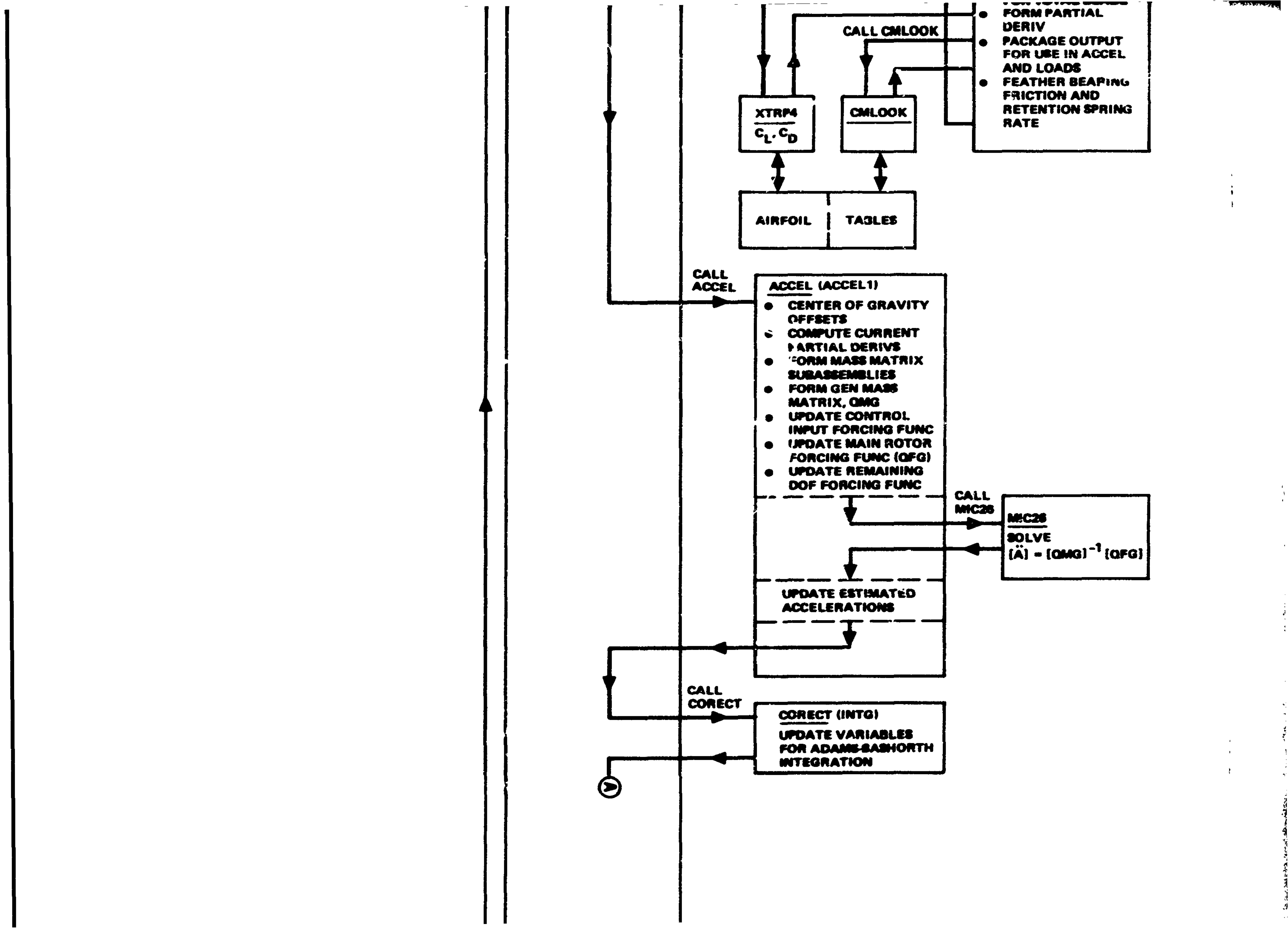
Figure 1-1. REXOR TRIM Operation to FLY Sequence (Sheet 1 of 2)



CALL TORS1
TORS1
BLADE INTEGRATION DATA
CALL BIRD1
BIRD1
COMPUTE FIXED CONTROL GEOMETRY INERTIAS, ZERO INTEGRATION STORAGE
CALL BMOVE
BMOVE
UPDATE BLADE CALC MODAL VARIABLE FROM INITIAL ZERO DOF VALUES
CALL ETORO1
ETORO1
ZERO ACCUMULATORS
SET CONSTANTS
CALL TRIM
TRIM
SET INPUT OPTIONS FROM RA SET
SET INITIAL CONTROL INPUTS
SET INITIAL DOWNWASH
COMPUTE AIRFLOW GEOMETRY
COMPUTE SHAFT BENDING GEOMETRY
FUSELAGE AIRFLOW
HUB ANGLE OF ATTACK AND YAW
HUB AIR ANGLES GEOMETRY
HUB INERTIAL ROTATION RATES
ZERO ACCELERAT STORAGE
CALL DERIV
DERIV
UPDATE PRINCIPAL REFERENCE SET
(CONT)
FROM END OF MAIN



HUB AIR ANGLES GEOMETRY
HUB INERTIAL ROTATION RATES
GRAVITY VECTOR AT HUB
ZERO ACCELERAT STORAGE
CALL DERIV
DERIV
UPDATE PRINCIPAL REFERENCE SET W AND W/O GRAVITY
DERIVF (DERIV)
UPDATE FUSELAGE SET ACCEL W AND W/O GRAVITY AND FUSELAGE VELOCITY
COMPUTE UPDATE CONTROL COLLECTIVE AND CYCLIC ACCEL FROM SP ACCEL
CALL LOADS
LOADS (LOADS1)
RESOLVE MR LOADS TO NON ROT. COORD
COMPUTE DOWNWASH FUNCTIONS
TAIL ROTOR AERO
PROP AERO
SUM ALL LOADS AT FUSELAGE REF.
CALL SWEEP
SWEEP
CURRENT BLADE POSITION GEOMETRY
COORDINATE TRANS-FORM STRINGS (XTERMO)
RELATIVE WIND
FORM GEN MASSES FOR TOTAL BLADE
FORM GEN FORCES
FORM PARTIAL DERIV
PACKAGE OUTPUT FOR USE IN ACCEL AND LOADS
FEATHER BEARING FRICTION AND RETENTION SPRING RATE
CALL XTRP4
CALL CMLOOK
XTRP4
C_L, C_D
CMLOOK
AIRFOIL
TABLES
CALL ACCEL
ACCEL (ACCEL1)
CENTER OF GRAVITY



FORM PARTIAL DERIV
PACKAGE OUTPUT FOR USE IN ACCEL AND LOADS
FEATHER BEARING FRICTION AND RETENTION SPRING RATE
CALL CMLOOK
XTRP4
C_L, C_D
CMLOOK
AIRFOIL
TABLES
CALL ACCEL
ACCEL (ACCEL1)
CENTER OF GRAVITY OFFSETS
COMPUTE CURRENT PARTIAL DERIVS
FORM MASS MATRIX SUBASSEMBLIES
FORM GEN MASS MATRIX, QMG
UPDATE CONTROL INPUT FORCING FUNC
UPDATE MAIN ROTOR FORCING FUNC (QFG)
UPDATE REMAINING DOF FORCING FUNC
CALL MIC26
MIC26
SOLVE
$[\ddot{A}] = [QMG]^{-1} [QFG]$
UPDATE ESTIMATED ACCELERATIONS
CALL CORECT
CORECT (INTG)
UPDATE VARIABLES FOR ADAMS-BASHORTH INTEGRATION
A

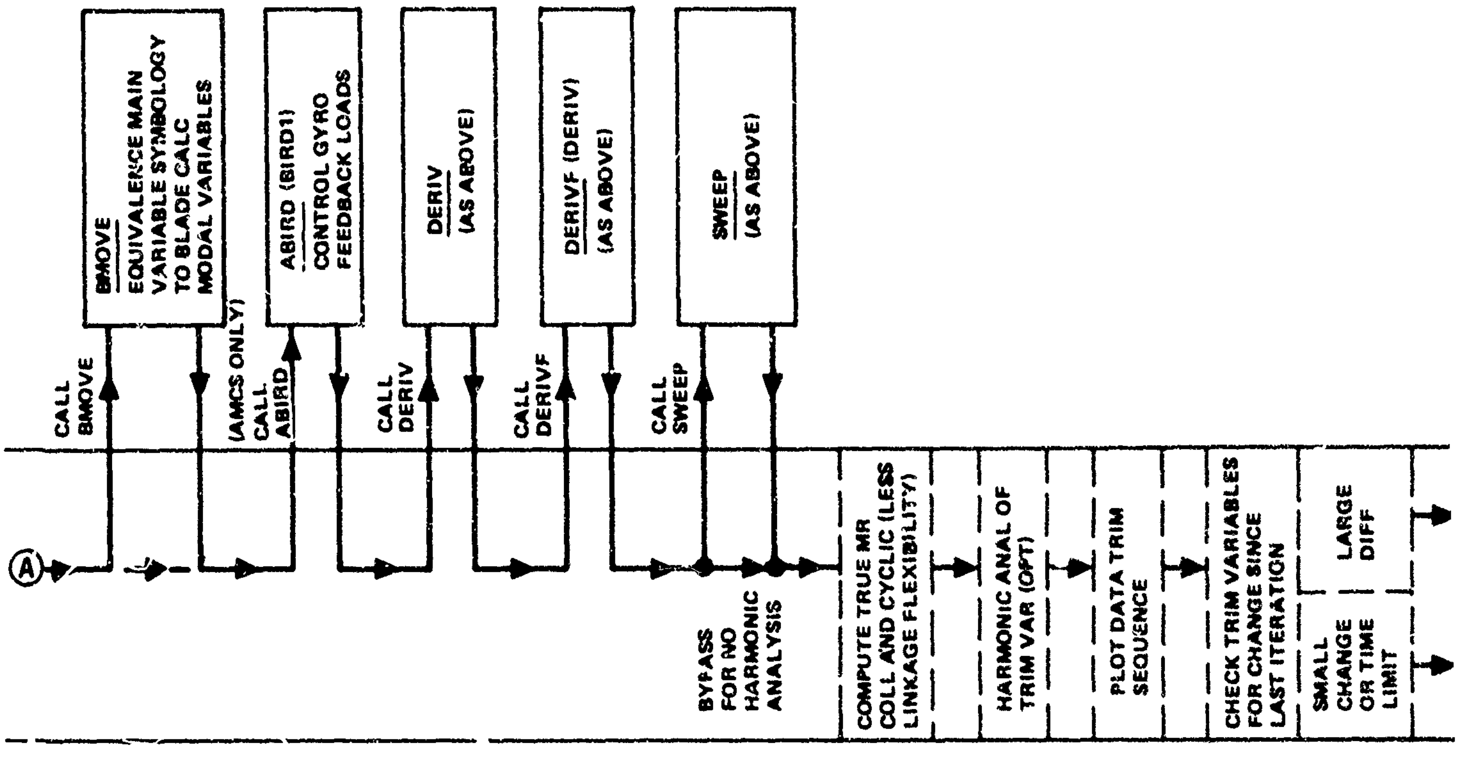


Figure 1-1. REXOR TRIM Operation o FLY Sequence (Sheet 2 of 2)

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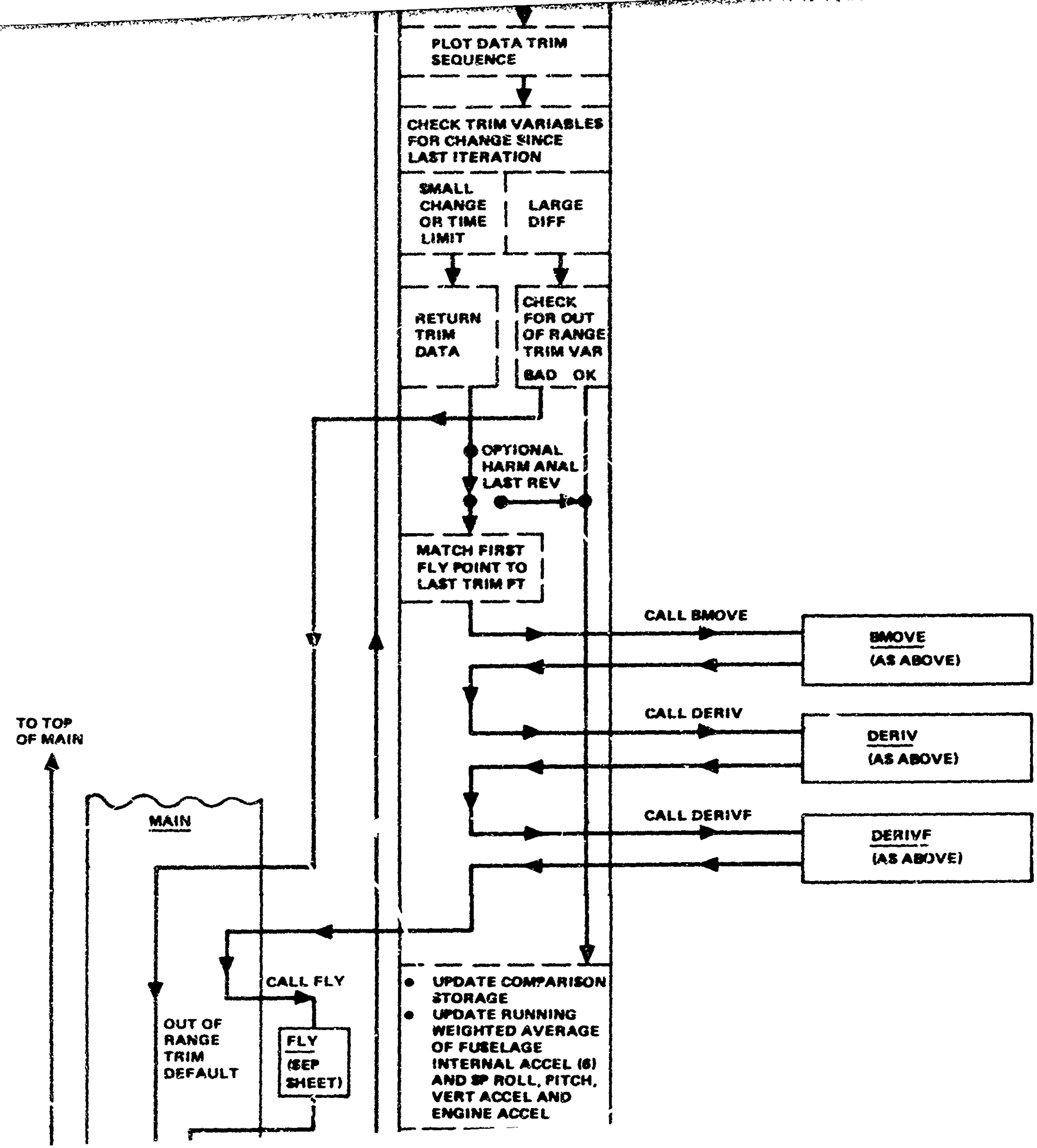
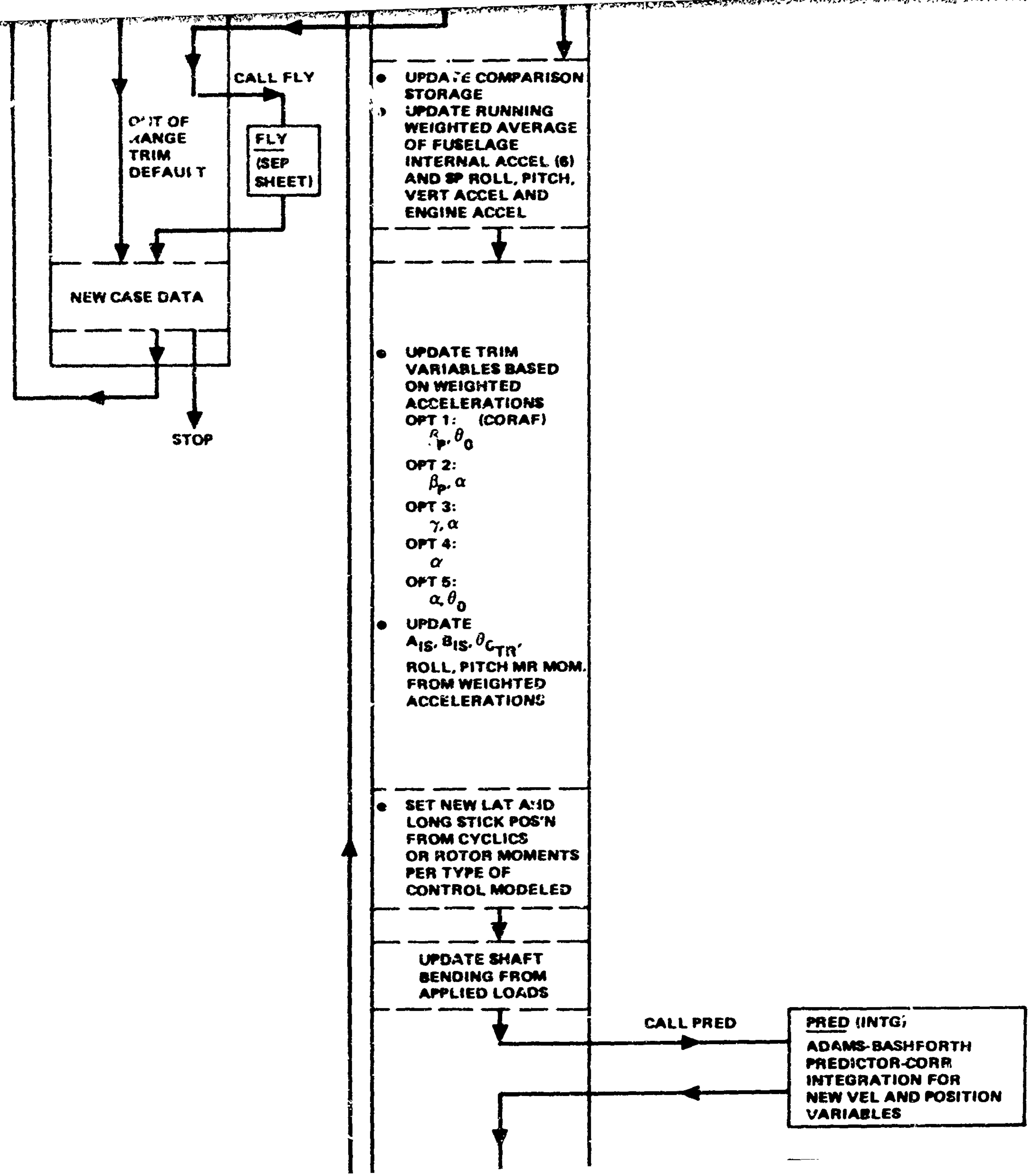
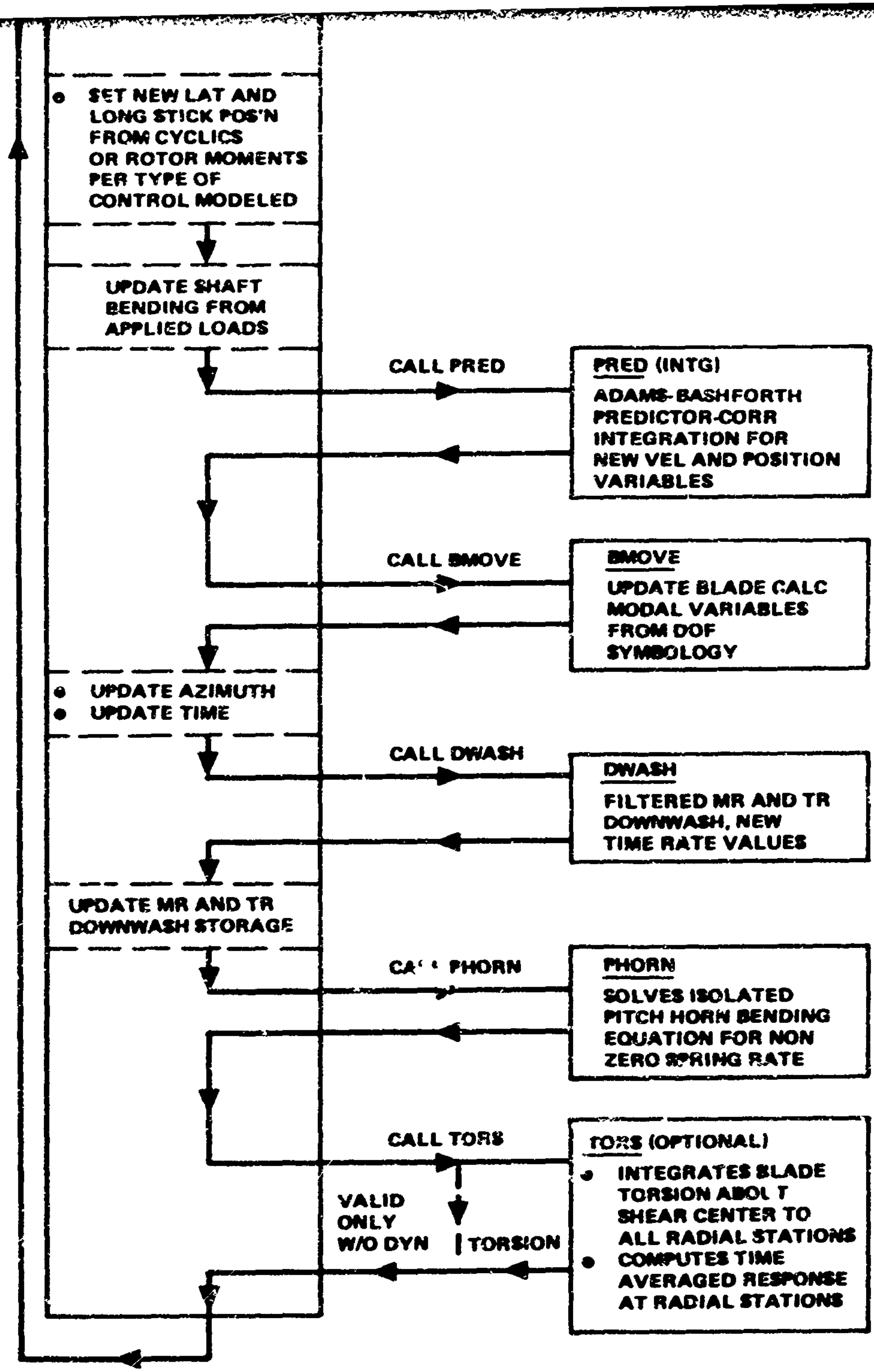


PLOT DATA TRIM SEQUENCE
CHECK TRIM VARIABLES FOR CHANGE SINCE LAST ITERATION
SMALL CHANGE OR TIME LIMIT
LARGE DIFF
RETURN TRIM DATA
CHECK FOR OUT OF RANGE TRIM VAR
BAD
OK
OPTIONAL HARM ANAL LAST REV
MATCH FIRST FLY POINT TO LAST TRIM PT
CALL BMOVE
BMOVE
(AS ABOVE)
CALL DERIV
DERIV
(AS ABOVE)
CALL DERIVF
DERIVF
(AS ABOVE)
TO TOP OF MAIN
MAIN
CALL FLY
FLY
(SEP SHEET)
OUT OF RANGE TRIM DEFAULT
UPDATE COMPARISON STORAGE
UPDATE RUNNING WEIGHTED AVERAGE OF FUSELAGE INTERNAL ACCEL (6) AND SP ROLL, PITCH, VERT ACCEL AND ENGINE ACCEL



CALL FLY
OUT OF RANGE TRIM DEFAULT
FLY (SEP SHEET)
NEW CASE DATA
STOP
UPDATE COMPARISON STORAGE
UPDATE RUNNING WEIGHTED AVERAGE OF FUSELAGE INTERNAL ACCEL (6) AND SP ROLL, PITCH, VERT ACCEL AND ENGINE ACCEL
UPDATE TRIM VARIABLES BASED ON WEIGHTED ACCELERATIONS
OPT 1: (CORAF) β_p, θ_0
OPT 2: β_p, α
OPT 3: γ, α
OPT 4: α
OPT 5: α, θ_0
UPDATE $A_{IS}, B_{IS}, \theta_{C_{TR}}$, ROLL, PITCH MR MOM. FROM WEIGHTED ACCELERATIONS
SET NEW LAT AND LONG STICK POS'N FROM CYCLICS OR ROTOR MOMENTS PER TYPE OF CONTROL MODELED
UPDATE SHAFT BENDING FROM APPLIED LOADS
CALL PRED
PRED (INTG)
ADAMS-BASHFORTH PREDICTOR-CORR INTEGRATION FOR NEW VEL AND POSITION VARIABLES


• SET NEW LAT AND LONG STICK POS'N FROM CYCLICS OR ROTOR MOMENTS PER TYPE OF CONTROL MODELED
UPDATE SHAFT BENDING FROM APPLIED LOADS
CALL PRED
PRED (INTG)
ADAMS-BASHFORTH PREDICTOR-CORR INTEGRATION FOR NEW VEL AND POSITION VARIABLES
CALL BMOVE
BMOVE
UPDATE BLADE CALC MODAL VARIABLES FROM DOF SYMBOLOGY
• UPDATE AZIMUTH
• UPDATE TIME
CALL DWASH
DWASH
FILTERED MR AND TR DOWNWASH, NEW TIME RATE VALUES
UPDATE MR AND TR DOWNWASH STORAGE
PHORN
SOLVES ISOLATED PITCH HORN BENDING EQUATION FOR NON ZERO SPRING RATE
CALL TORS
TORS (OPTIONAL)
• INTEGRATES BLADE TORSION ABOUT SHEAR CENTER TO ALL RADIAL STATIONS
• COMPUTES TIME AVERAGED RESPONSE AT RADIAL STATIONS
VALID ONLY W/O DYN TORSION

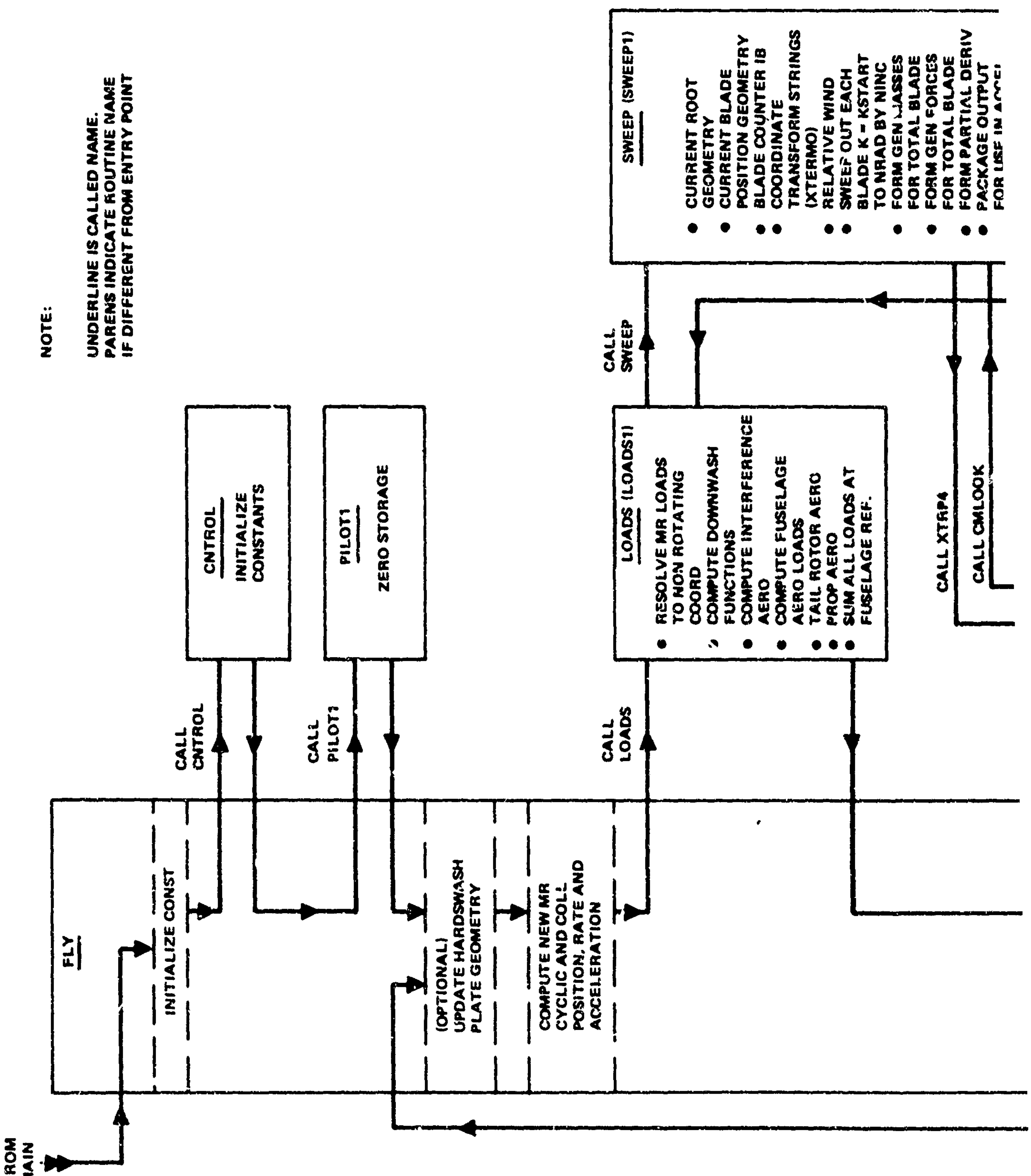


Figure 1-2. REXOR FLY (Sheet 1 of 2)

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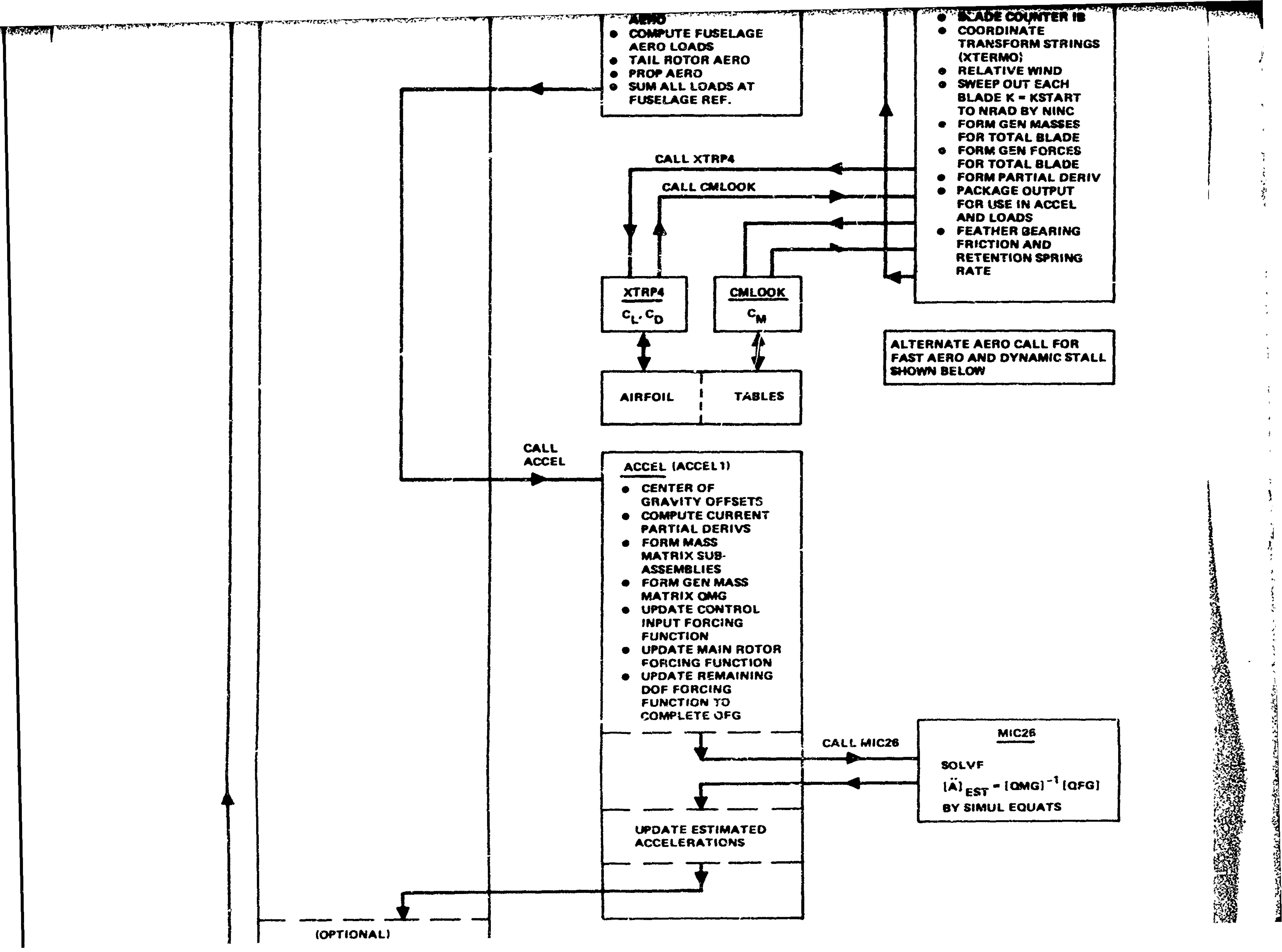
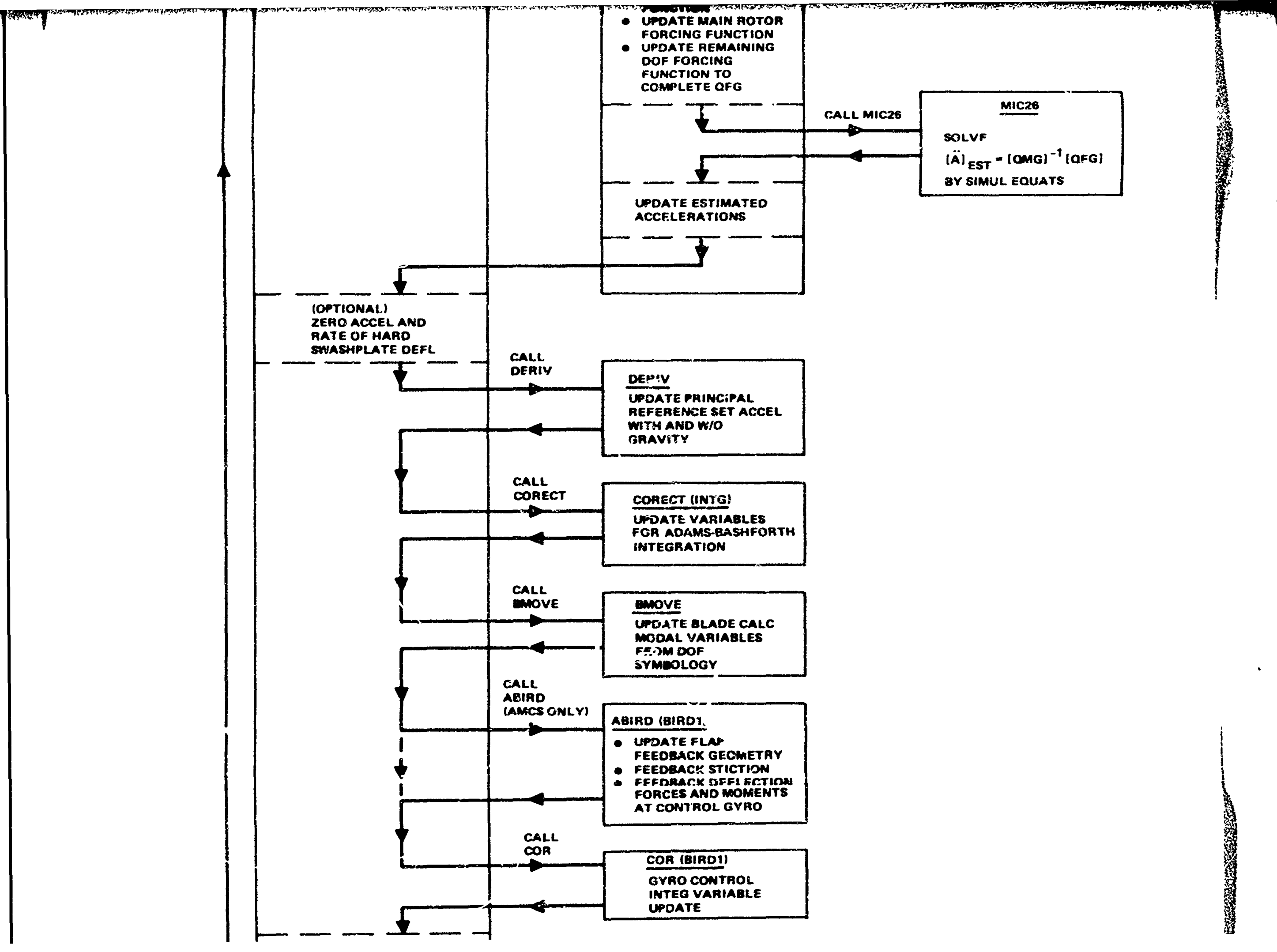
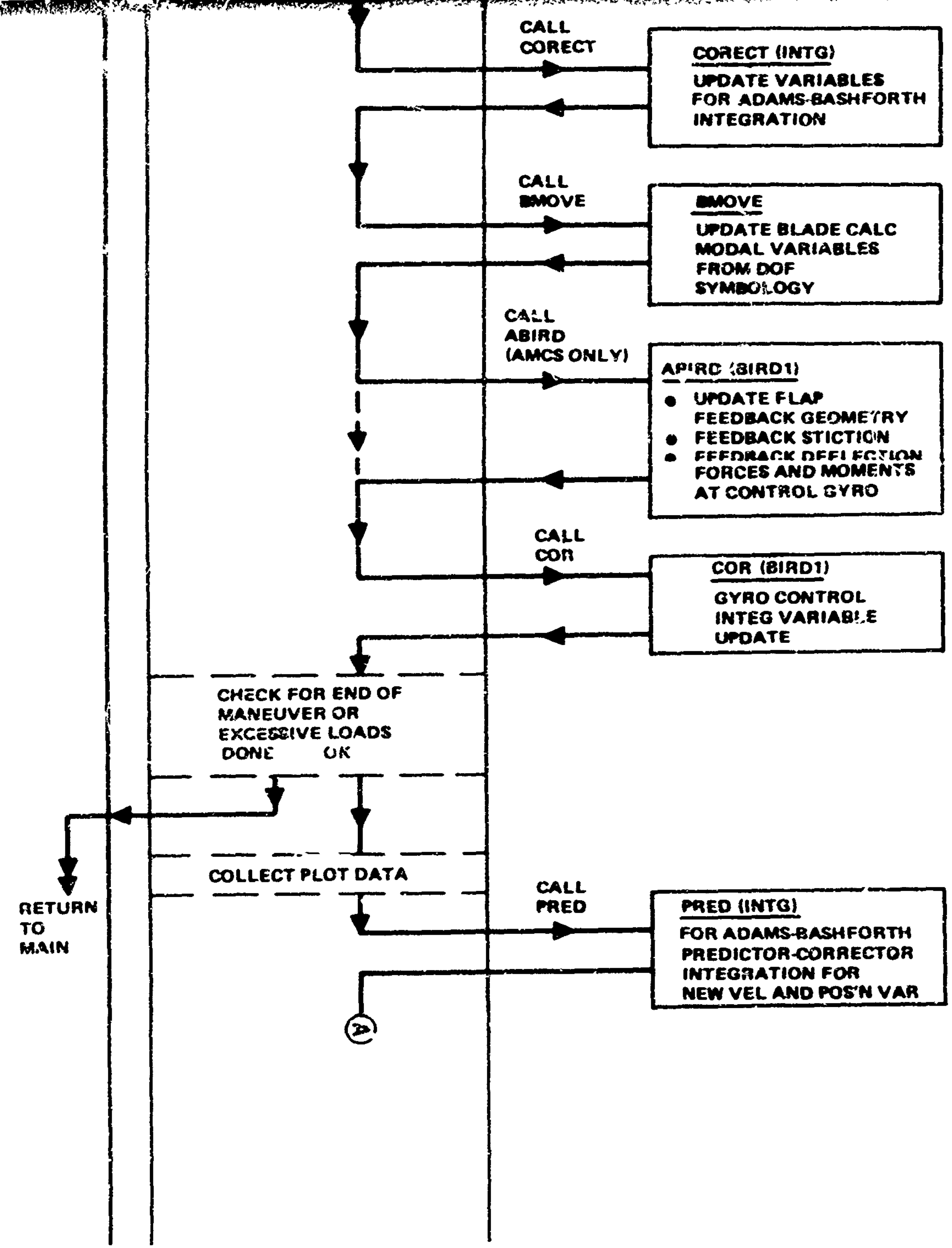

AERO
• COMPUTE FUSELAGE AERO LOADS
• TAIL ROTOR AERO
• PROP AERO
• SUM ALL LOADS AT FUSELAGE REF.
BLADE COUNTER IB
• COORDINATE TRANSFORM STRINGS (XTERMO)
• RELATIVE WIND
• SWEEP OUT EACH BLADE K = KSTART TO NRAD BY NINC
• FORM GEN MASSES FOR TOTAL BLADE
• FORM GEN FORCES FOR TOTAL BLADE
• FORM PARTIAL DERIV
• PACKAGE OUTPUT FOR USE IN ACCEL AND LOADS
• FEATHER BEARING FRICTION AND RETENTION SPRING RATE
CALL XTRP4
CALL CMLOOK
XTRP4
C_L, C_D
CMLOOK
C_M
AIRFOIL
TABLES
ALTERNATE AERO CALL FOR FAST AERO AND DYNAMIC STALL SHOWN BELOW
CALL ACCEL
ACCEL (ACCEL1)
• CENTER OF GRAVITY OFFSETS
• COMPUTE CURRENT PARTIAL DERIVS
• FORM MASS MATRIX SUB-ASSEMBLIES
• FORM GEN MASS MATRIX QMG
• UPDATE CONTROL INPUT FORCING FUNCTION
• UPDATE MAIN ROTOR FORCING FUNCTION
• UPDATE REMAINING DOF FORCING FUNCTION TO COMPLETE QFG
CALL MIC26
MIC26
SOLVF
$[\ddot{A}]_{EST} = [QMG]^{-1}[QFG]$
BY SIMUL EQUATS
UPDATE ESTIMATED ACCELERATIONS
(OPTIONAL)



FUNCTION
• UPDATE MAIN ROTOR FORCING FUNCTION
• UPDATE REMAINING DOF FORCING FUNCTION TO COMPLETE QFG
CALL MIC26
MIC26
SOLVF
$[\ddot{A}]_{EST} = [OMG]^{-1}[QFG]$
BY SIMUL EQUATS
UPDATE ESTIMATED ACCELERATIONS
(OPTIONAL) ZERO ACCEL AND RATE OF HARD SWASHPLATE DEFL
CALL DERIV
DERIV
UPDATE PRINCIPAL REFERENCE SET ACCEL WITH AND W/O GRAVITY
CALL CORECT
CORECT (INTG)
UPDATE VARIABLES FOR ADAMS-BASHFORTH INTEGRATION
CALL BMOVE
BMOVE
UPDATE BLADE CALC MODAL VARIABLES FROM DOF SYMBOLOGY
CALL ABIRD (AMCS ONLY)
ABIRD (BIRD1)
• UPDATE FLAP FEEDBACK GEOMETRY
• FEEDBACK STICTION
• FEEDBACK DEFLECTION FORCES AND MOMENTS AT CONTROL GYRO
CALL COR
COR (BIRD1)
GYRO CONTROL INTEG VARIABLE UPDATE


CALL CORECT
CORECT (INTG)
UPDATE VARIABLES FOR ADAMS-BASHFORTH INTEGRATION
CALL BMOVE
BMOVE
UPDATE BLADE CALC MODAL VARIABLES FROM DOF SYMBOLOGY
CALL ABIRD (AMCS ONLY)
ABIRD (BIRD1)
UPDATE FLAP FEEDBACK GEOMETRY
FEEDBACK STICTION
FEEDBACK DEFLECTION FORCES AND MOMENTS AT CONTROL GYRO
CALL COR
COR (BIRD1)
GYRO CONTROL INTEG VARIABLE UPDATE
CHECK FOR END OF MANEUVER OR EXCESSIVE LOADS
DONE
OK
RETURN TO MAIN
COLLECT PLOT DATA
CALL PRED
PRED (INTG)
FOR ADAMS-BASHFORTH PREDICTOR-CORRECTOR INTEGRATION FOR NEW VEL AND POS'N VAR
A

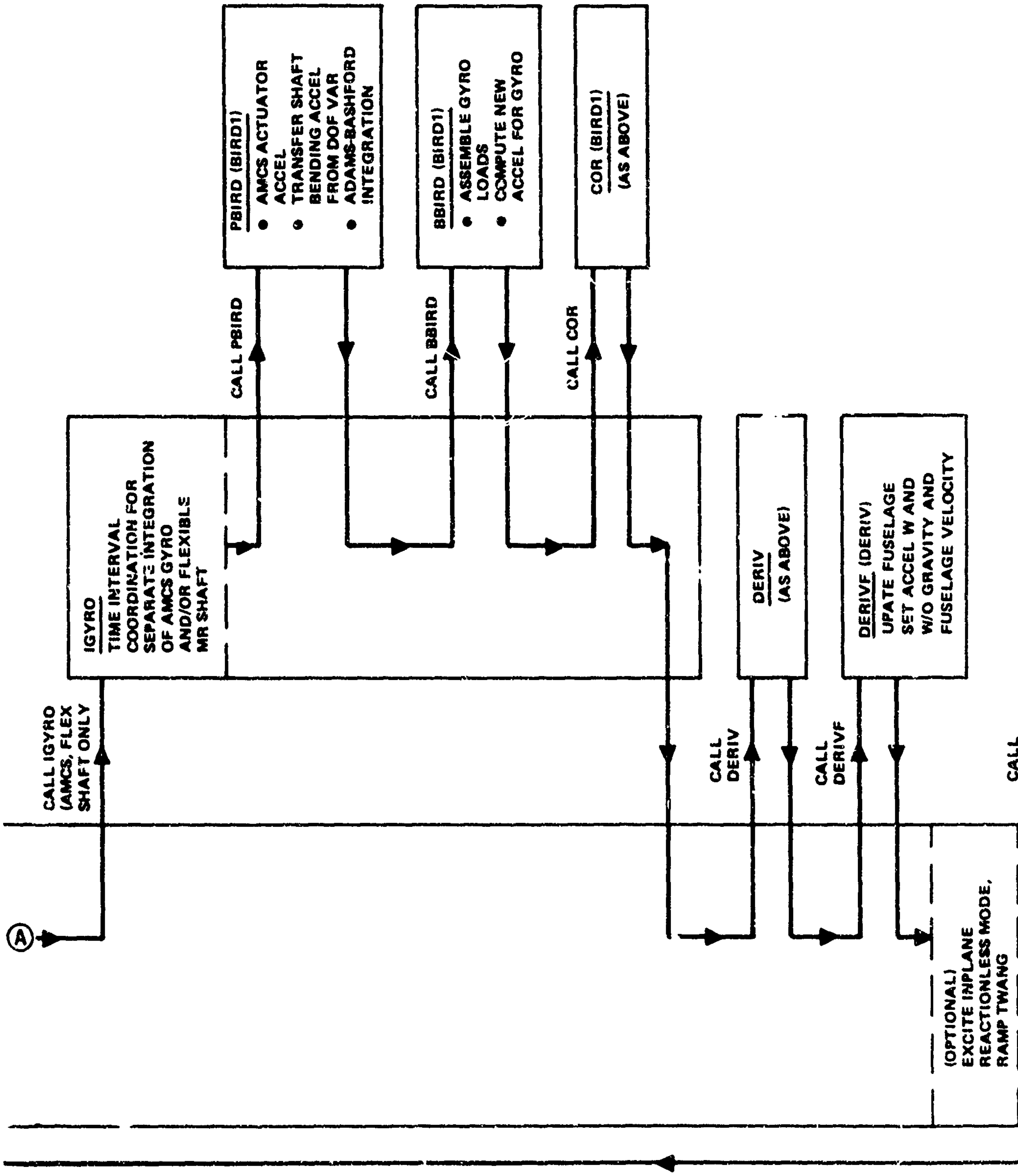


Figure 1-2. REXOR FLY (Sheet 2 of 2)

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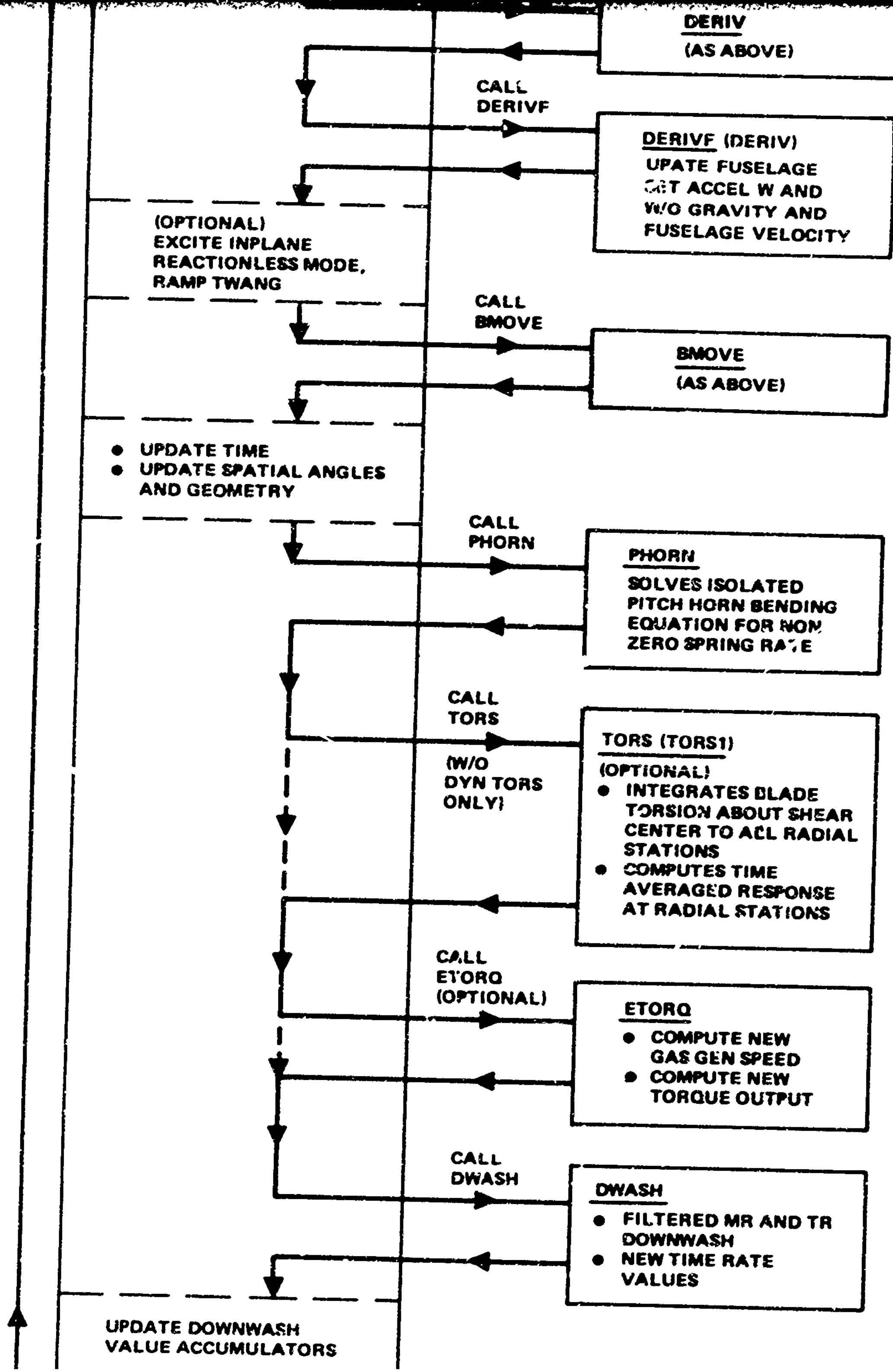
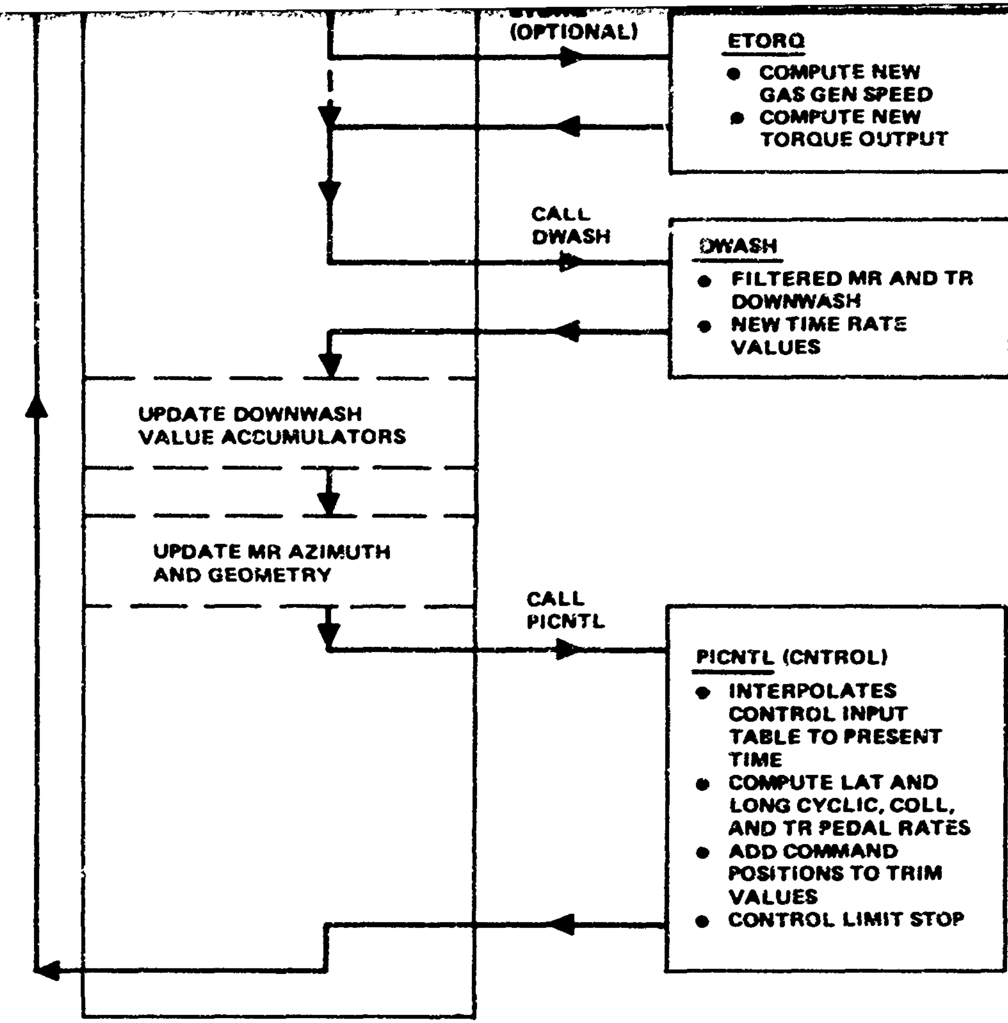
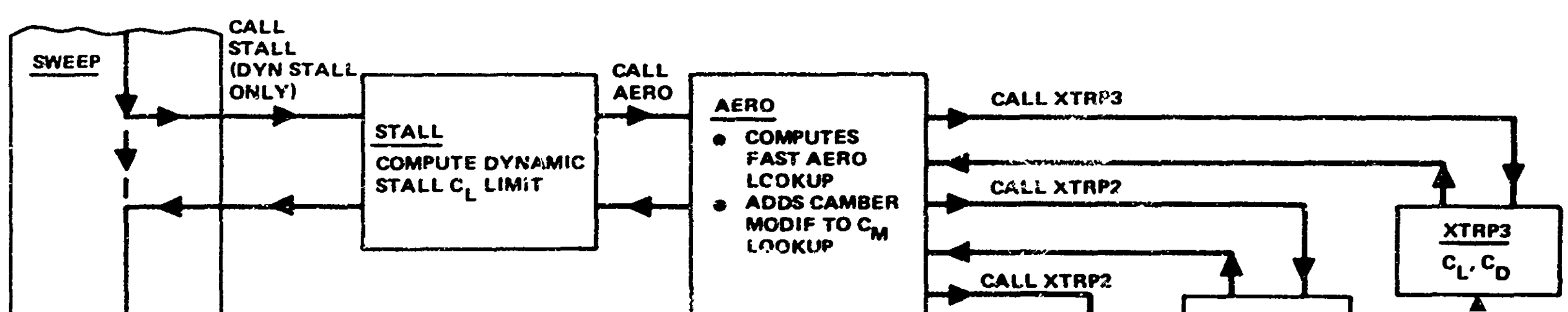
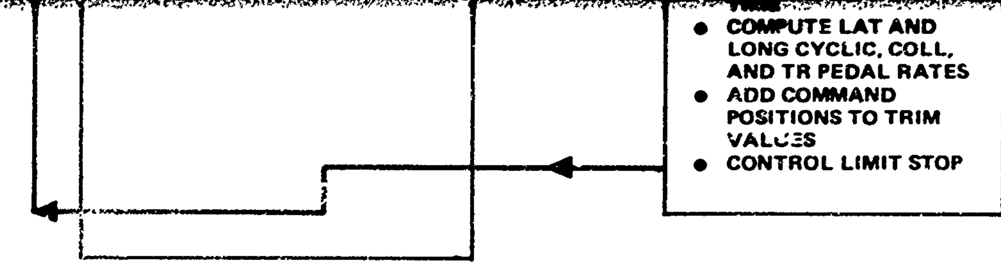


DERIV
(AS ABOVE)
CALL
DERIVF
DERIVF (DERIV)
UPATE FUSELAGE
GET ACCEL W AND
W/O GRAVITY AND
FUSELAGE VELOCITY
(OPTIONAL)
EXCITE INPLANE
REACTIONLESS MODE,
RAMP TWANG
CALL
BMOVE
BMOVE
(AS ABOVE)
• UPDATE TIME
• UPDATE SPATIAL ANGLES
AND GEOMETRY
CALL
PHORN
PHORN
SOLVES ISOLATED
PITCH HORN BENDING
EQUATION FOR NON
ZERO SPRING RATE
CALL
TORS
(W/O
DYN TORS
ONLY)
TORS (TORS1)
(OPTIONAL)
• INTEGRATES BLADE
TORSION ABOUT SHEAR
CENTER TO ALL RADIAL
STATIONS
• COMPUTES TIME
AVERAGED RESPONSE
AT RADIAL STATIONS
CALL
ETORQ
(OPTIONAL)
ETORQ
• COMPUTE NEW
GAS GEN SPEED
• COMPUTE NEW
TORQUE OUTPUT
CALL
DWASH
DWASH
• FILTERED MR AND TR
DOWNWASH
• NEW TIME RATE
VALUES
UPDATE DOWNWASH
VALUE ACCUMULATORS



ALTERNATE AERO DETAIL





ALTERNATE AERO DETAIL

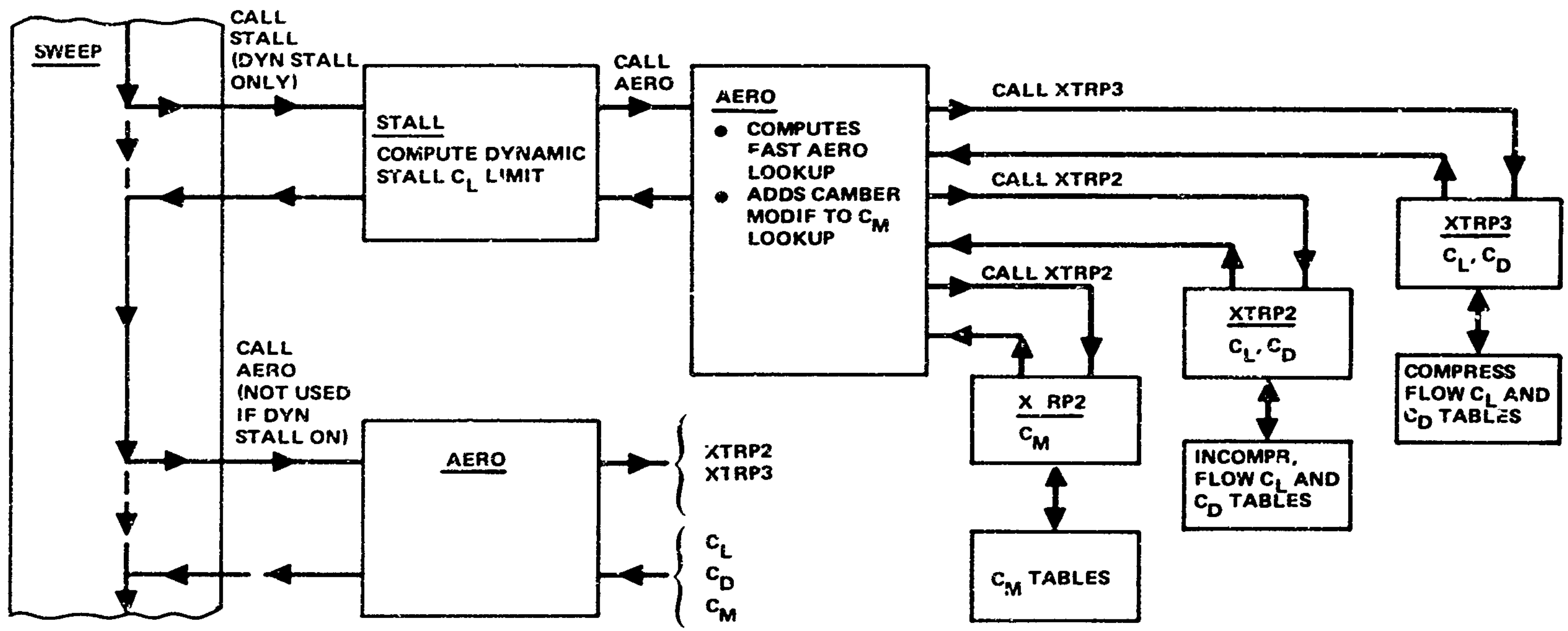


TABLE 1-1. REXOR ROUTINES		
	Routine Name	Entry Points
1.	ACCEL1	ACCEL1, ACCEL
2.	AERO	AERO
3.	BIRD1	BIRD1, PBIRD, ABIRD, BBIRD, COR
4.	BMOVE	BMOVE,
5.	BSCALE	BSCALE
6.	CMLOOK	CMLOOK
7.	CNTROL	CNTROL, APCNTL, PICNTL
8.	COULOM	COULOM
9.	DERIV	DERIV, DERIVF
10.	DWASH	DWASH
11.	ETORQ1	ETORQ1, ETORQ
12.	FLY	FLY
13.	HARM1	HARM1, HARM, HARM2
14.	IGYRO	IGYRO
15.	INTG	INTG, PRED, CORECT
16.	LOADS1	LOADS1, LOADS
17.	LSTDAT	LSTDAT
18.	MAIN	(CONTROLLING ROUTINE)
19.	MIC26	MIC26
20.	MINVR	MINVR
21.	MPRNT	MPRNT
22.	PDATE	PDATE
23.	PHORN	PHORN
24.	PILOTA	PILOTA, PILOTI
25.	PRINT1	PRINT1, PRINT
26.	PROP	(BLOCK DATA)
27.	RCPLOT	RCPLOT
28.	READIN	READIN
29.	STALL	STALL

TABLE 1-1 - Continued

Routine Name		Entry Points	
30.	SWEEP1	SWEEP1, SWEEP	
31.	TORS1	TORS1, TORS	
32.	TRIM	TRIM	
33.	TRMPUN	TRMPUN, DSHIFT	
34.	XTERM0	XTERM0, XTERM1, XTERM2, XTERM3, XTERM4, XTERM5, XTERM6, XTERM7, XTERM8, XTERM9, XTERMA, XTERMC, XTERMD, XTERME	
35.	XTRP1	XTRP1	
36.	XTRP2	XTRP2	
37.	XTRP3	XTRP3	
38.	CMA	(BLOCK DATA)	
39.	CMAM	(BLOCK DATA)	
40.	CLAT	(BLOCK DATA)	
41.	CLATM	(BLOCK DATA)	
42.	CDAT	(BLOCK DATA)	
43.	CDATM	(BLOCK DATA)	
44.	XTRP	XTRP	
45.	XTRP4	XTRP4	
46.	XTRPCA	XTRPCA	
47.	CMTICL	(BLOCK DATA)	SIMILAR BLOCKS -2 TO -7
48.	CMTICD	(BLOCK DATA)	
49.	CTISCL	(BLOCK DATA)	SIMILAR BLOCKS -2 TO -7
50.	CTISCD	(BLOCK DATA)	
51.	CMTICM	(BLOCK DATA)	
52.	CMT2CM	(BLOCK DATA)	

computation procedure known as REXOR. Therefore these subroutines are covered in detail, and matched to the symbology and equations of Volume I. Another class of subroutines contain computation subgroupings required by the routines just mentioned, or setup the integration and equation solving process. These routines are covered in less detail, but with enough explanatory material for the reader to see how the programming accomplishes the desired task. The last class of routines is one of utility functions such as plotting, printing and date. These entries are noted as to input-output function.

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The entry point ACCEL in conjunction with similar points LOADS and SWEEP form the computation nucleus of REXOR. ACCEL gathers the information to form the generalized mass and force matricies, and controls the acceleration update sequence. The majority of the development of Volume I, Section 6, except for blade geometry and summation, is coded in this entry.

As shown in Figure 1-3, the entry ACCEL collects the generalized masses and forces to proceed with determining acceleration terms. When REXOR is in the TRIM mode of operation, the mass and force equations are solved twice per pass in the subroutine. First, only the blade degree of freedom equations are solved for accelerations to be used in the time integration. Second, the entire degree of freedom acceleration vector is solved. The TRIM acceleration terms are used from this second trial to readjust the controls to iterate a stable trimmed flight condition. Two trials are needed so that the blade accelerations used for blade integrations are not contaminated with incorrect accelerations from the other degrees of freedom. In the FLY mode the entire acceleration vector is developed and integrated. Therefore, the solution sequence takes place only once per pass in ACCEL.

The generalized masses are coded as QMG and the generalized forces are coded as the QFG array. The notation of these arrays is locked to the problem variable names as given in Table 1-2. The coding may be traced back to Volume I by use of this table, keeping in mind that the mass matrix is symmetrical. For example QMG(21, 16) is $M_{X_H \beta_{PHN}}$ from Volume I, Section 6.9.

The generalized masses are assembled from precomputed inertias, partial derivatives, subcomputations and results from SWEEP. The inertias, center of gravity offsets, and masses can be directly read from the code noting

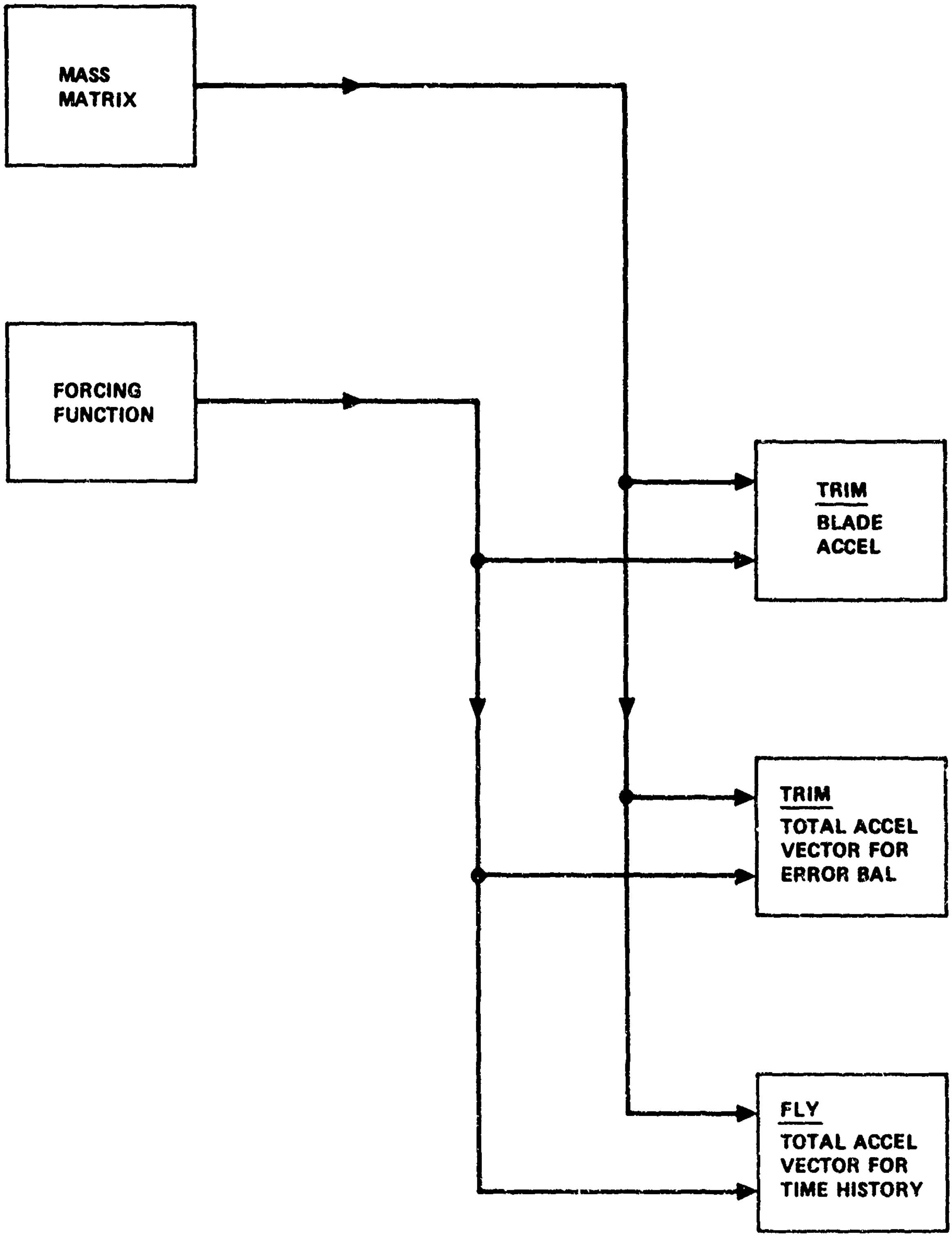

Figure 1-3. ACCEL Computation Flow.

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Row	Degree of Freedom	
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3	A_{31}	
4	β_{PH1}	
5	A_{12}	Blade 2
6	A_{22}	
7	A_{32}	
8	β_{PH2}	
9	A_{13}	Blade 3
10	A_{23}	
11	A_{33}	
12	β_{PH3}	
13	A_{14}	Blade 4
14	A_{24}	
15	A_{34}	
16	β_{PH4}	
17	ϕ_{SP}	Swash Plate
18	θ_{SP}	
19	Z_{SP}	
20	Ψ_{R}	Rotor Azimuth
21	X_{H}	Principal Ref. Axis
22	Y_{H}	
23	Z_{H}	
24	ϕ_{H}	
25	θ_{H}	
26	ψ_{H}	
27	ϕ_{S}	Shaft Bending
28	θ_{S}	
Gyro Variables ϕ_G, θ_G Are Solved For Independently		

that F stands for fuselage and B stands for principal reference axis (H for hub). The B notation stems from the old reference B for Body. BAR means ($^-$), and identifies a center-of-gravity offset.

Partial derivatives are grouped, and use a six-letter identifier generally starting with P for partial. The sequence of letters gives the partial derivative numerator and denominator. For example PZFPYB is partial Z fuselage, with respect to partial Y body or $\partial Z_F/\partial Y_H$. The six-letter limit calls for improvisation. PHFPSB is $\partial \phi_F/\partial \Psi_H$ and THFTHB is $\partial \theta_F/\partial \theta_H$. Terms involving blade partial derivatives which require spanwise blade integration are transferred from SWEEP in the array F which is described under the heading SWEEP1. A derivative listing is given in Table 1-3.

A number of subcomputations grouped as BM---- and CM---- are made for body (hub) mass and control mass respectively. The mnemonics used are not directly readable, but should be referenced to the QMG calculations for meaning.

The QFG array is assembled from blade data (also in the F array mentioned), data from LOADS and swashplate loads. The latter are developed within ACCEL from Volume I, Section 6.10. The array QLOADS from LOADS is the non-main rotor aerodynamic loads as developed in Volume I, Section 7.4. The QFG components involving these loads are assembled with the appropriate inertias, partials, etc., as the equations require.

Using the completed QMG and QFG arrays, a new correction acceleration vector DELA is found from the subroutine MIC26. DELA then is added to the running estimate acceleration vector YDD. The YDD array has the same ordering as given in Table 1-2.

Due to the method of introducing the gravity vector, discussed in Volume I, Section 5.5.1, gravity acceleration as well as maneuvering loads will appear on the vector triad YDD(21, 22, 23). These accelerations are balanced by the force vector, thus propagating the acceleration due to gravity throughout the problem. These accelerations do not need to be integrated for use elsewhere, therefore the positions YD(21, 22, 23) are used for the corresponding accelerations without gravity. The multiple use of the YDD, YD, Y array is not limited to the gravity terms. An array summary is given in Table 1-4 for dimensions greater than 20, and will be referred to under subsequent headings. No foldover exists for dimensions less than 21, and Table 1-2 may be referenced.

1.3.2 AERO

The subroutine AERO is called in the Fast Aero main rotor aerodynamic data lookup procedure. The operations of this procedure are developed in Volume I, Section 7.2.4; Section 4 of this volume; and Volume III, Section 3.3.7.3. This Fast Aero procedure uses airfoil data which has been interpolated into equally spaced increments, and reduced only to the types and sections of blade data actually needed. The set currently in REXOR is

TABLE 1-3. PARTIAL DERIVATIVES IN ACCEL

<u>Shaft Bending</u>

Symbology FORTRAN Name

$$\left\{\frac{\partial r_{OF}}{\partial \phi_S}\right\} = \left\{\begin{matrix} - \\ \text{PYFPPS} = \text{YPHIF} = \text{RA(365)} \\ - \end{matrix}\right\} \quad (1\text{-}1)$$

$$\left\{\frac{\partial r_{OF}}{\partial \theta_S}\right\} = \left\{\begin{matrix} \text{XTHTF} = \text{RA(364)} \\ - \\ - \end{matrix}\right\} \quad (1\text{-}2)$$

$$\left\{\frac{\partial \zeta_F}{\partial \phi_S}\right\} = \left\{\begin{matrix} \text{PHFPHS} \\ - \\ \text{PSIPHS} \end{matrix}\right\} \quad (1\text{-}3)$$

$$\left\{\frac{\partial \zeta_F}{\partial \theta_S}\right\} = \left\{\begin{matrix} \text{PHFTHS} \\ \text{THFTHS} \\ \text{PSITHS} \end{matrix}\right\} \quad (1\text{-}4)$$

<u>Swashplate Motions</u>

$$\left[\frac{\partial \zeta_{SP}}{\partial \zeta_{SP}}\right] = \left[\begin{matrix} \text{PFGGF}, & \text{PFGGD}, & - \\ \text{PTGGK}, & \text{PTGGD}, & - \\ \text{PSIGGK}, & \text{PSIGGD}. & - \end{matrix}\right] \quad (1\text{-}5)$$

$$\frac{\partial Z_{OSP}}{\partial Z_{SP}} = 1 \quad (1\text{-}6)$$

TABLE 1-3 - Continued

Swashplate Motions (Continued)

Symbology		FORTRAN Name	
$\frac{\partial \phi_{FN}}{\partial \phi_{SP}}$	=	PFGK(I)	(1-7)
$\frac{\partial \phi_{FN}}{\partial \theta_{SP}}$	=	PFGD(I)	(1-8)
$\frac{\partial \phi_{FN}}{\partial \zeta_{SP}}$	=	PFHG(I)	(1-9)

Pitch Horn Bending

$$\frac{\partial \phi_{FN}}{\partial \beta_{PHn}} = \text{PFEPH} \qquad (1\text{-}10)$$

Principal Axis Motions

$$\left[\frac{\partial r_{OBLn}}{\partial r_H}\right] = \begin{bmatrix} \text{PXRXB(I)}, & \text{PXRYB(I)}, & - \\ \text{PYRXB(I)}, & \text{PYRYB(I)}, & - \\ - , & - , & \text{PZRZB(I)} \end{bmatrix} \qquad (1\text{-}11)$$

$$\left[\frac{\partial r_{OF}}{\partial r_H}\right] = \begin{bmatrix} \text{PXFPXB}, & \text{PXFPYB}, & \text{PXFPZB} \\ \text{PYFPXB}, & \text{PYFPYB}, & \text{PYFPZB} \\ \text{PZFPXB}, & \text{PZFPYB}, & \text{PZFPZB} \end{bmatrix} \qquad (1\text{-}12)$$

TABLE 1-1. REXOR ROUTINES		
	Routine Name	Entry Points
1.	ACCEL1	ACCEL1, ACCEL
2.	AERO	AERO
3.	BIRD1	BIRD1, PBIRD, ABIRD, BBIRD, COR
4.	BMOVE	BMOVE,
5.	BSCALE	BSCALE
6.	CMLOOK	CMLOOK
7.	CNTROL	CNTROL, APCNTL, PICNTL
8.	COULOM	COULOM
9.	DERIV	DERIV, DERIVF
10.	DWASH	DWASH
11.	ETORQ1	ETORQ1, ETORQ
12.	FLY	FLY
13.	HARM1	HARM1, HARM, HARM2
14.	IGYRO	IGYRO
15.	INTG	INTG, PRED, CORECT
16.	LOADS1	LOADS1, LOADS
17.	LSTDAT	LSTDAT
18.	MAIN	(CONTROLLING ROUTINE)
19.	MIC26	MIC26
20.	MINVR	MINVR
21.	MPRNT	MPRNT
22.	PDATE	PDATE
23.	PHORN	PHORN
24.	PILOTA	PILOTA, PILOTI
25.	PRINT1	PRINT1, PRINT
26.	PROP	(BLOCK DATA)
27.	RCPLOT	RCPLOT
28.	READIN	READIN
29.	STALL	STALL

TABLE 1-1 - Continued

Routine Name		Entry Points	
30.	SWEEP1	SWEEP1, SWEEP	
31.	TORS1	TORS1, TORS	
32.	TRIM	TRIM	
33.	TRMPUN	TRMPUN, DSHIFT	
34.	XTERM0	XTERM0, XTERM1, XTERM2, XTERM3, XTERM4, XTERM5, XTERM6, XTERM7, XTERM8, XTERM9, XTERMA, XTERMC, XTERMD, XTERME	
35.	XTRP1	XTRP1	
36.	XTRP2	XTRP2	
37.	XTRP3	XTRP3	
38.	CMA	(BLOCK DATA)	
39.	CMAM	(BLOCK DATA)	
40.	CLAT	(BLOCK DATA)	
41.	CLATM	(BLOCK DATA)	
42.	CDAT	(BLOCK DATA)	
43.	CDATM	(BLOCK DATA)	
44.	XTRP	XTRP	
45.	XTRP4	XTRP4	
46.	XTRPCA	XTRPCA	
47.	CMTICL	(BLOCK DATA)	SIMILAR BLOCKS -2 TO -7
48.	CMTICD	(BLOCK DATA)	
49.	CTISCL	(BLOCK DATA)	SIMILAR BLOCKS -2 TO -7
50.	CTISCD	(BLOCK DATA)	
51.	CMTICM	(BLOCK DATA)	
52.	CMT2CM	(BLOCK DATA)	

computation procedure known as REXOR. Therefore these subroutines are covered in detail, and matched to the symbology and equations of Volume I. Another class of subroutines contain computation subgroupings required by the routines just mentioned, or setup the integration and equation solving process. These routines are covered in less detail, but with enough explanatory material for the reader to see how the programming accomplishes the desired task. The last class of routines is one of utility functions such as plotting, printing and date. These entries are noted as to input-output function.

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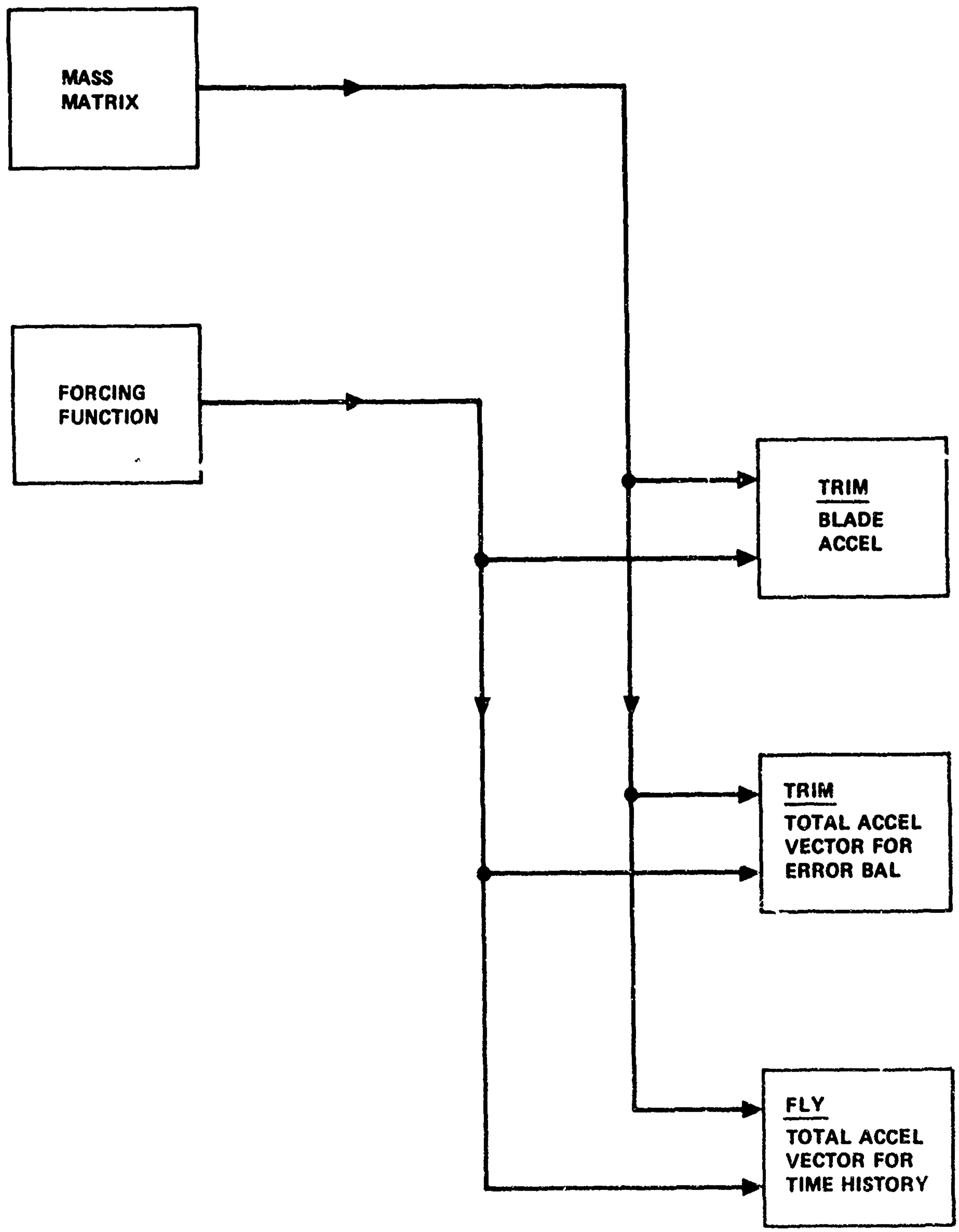

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10	A_{23}	
11	A_{33}	
12	β_{PH3}	
13	A_{14}	Blade 4
14	A_{24}	
15	A_{34}	
16	β_{PH4}	
17	ϕ_{SP}	Swash Plate
18	θ_{SP}	
19	Z_{SP}	
20	Ψ_R	Rotor Azimuth
21	X_H	Principal Ref. Axis
22	Y_H	
23	Z_H	
24	ϕ_H	
25	θ_H	
26	ψ_H	
27	ϕ_S	Shaft Bending
28	θ_S	

Gyro Variables ϕ_G, θ_G Are Solved For Independently

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Symbology | FORTRAN Name

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$$\left\{ \frac{\partial r_{OF}}{\partial \theta_S} \right\} = \left\{ \begin{matrix} \mathrm{XTHTF} = \mathrm{RA}(364) \\ - \\ - \end{matrix} \right\} \qquad (1\text{-}2)$$

$$\left\{ \frac{\partial \zeta_F}{\partial \phi_S} \right\} = \left\{ \begin{matrix} \mathrm{PHFPHS} \\ - \\ \mathrm{PSIPHS} \end{matrix} \right\} \qquad (1\text{-}3)$$

$$\left\{ \frac{\partial \zeta_F}{\partial \theta_S} \right\} = \left\{ \begin{matrix} \mathrm{PHFTHS} \\ \mathrm{THFTHS} \\ \mathrm{PSITHS} \end{matrix} \right\} \qquad (1\text{-}4)$$

<u>Swashplate Motions</u>

$$\left[\frac{\partial \zeta_{SP}}{\partial \zeta_{SP}} \right] = \left[\begin{matrix} \mathrm{PFGGF}, & \mathrm{PFGGD}, & - \\ \mathrm{PTGGK}, & \mathrm{PTGGD}, & - \\ \mathrm{PSIGGK}, & \mathrm{PSIGGD}. & - \end{matrix} \right] \qquad (1\text{-}5)$$

$$\frac{\partial z_{OSP}}{\partial z_{SP}} = 1 \qquad (1\text{-}6)$$

TABLE 1-3 - Continued

Swashplate Motions (Continued)

Symbology		FORTRAN Name	
$\frac{\partial\phi_{FN}}{\partial\phi_{SP}}$	=	PFGK(I)	(1-7)
$\frac{\partial\phi_{FN}}{\partial\theta_{SP}}$	=	PFGD(I)	(1-8)
$\frac{\partial\phi_{FN}}{\partial z_{SP}}$	=	PFHG(I)	(1-9)

Pitch Horn Bending

$$\frac{\partial\phi_{FN}}{\partial\beta_{PHn}} = \text{PFBPH} \tag{1-10}$$

Principal Axis Motions

$$\left[\frac{\partial r_{OBLn}}{\partial r_H}\right] = \begin{bmatrix} \text{PXRXB(I)}, & \text{PXRYB(I)}, & - \\ \text{PYRXB(I)}, & \text{PYRYB(I)}, & - \\ - , & - , & \text{PZRZB(I)} \end{bmatrix} \tag{1-11}$$

$$\left[\frac{\partial r_{OF}}{\partial r_H}\right] = \begin{bmatrix} \text{PXFPXB}, & \text{PXFPYB}, & \text{PXFPZB} \\ \text{PYFPXB}, & \text{PYFPYB}, & \text{PYFPZB} \\ \text{PZFPXB}, & \text{PZFPYB}, & \text{PZFPZB} \end{bmatrix} \tag{1-12}$$

TABLE 1-3 - Continued

Principal Axis Motions (Continued)

Symbology		FORTRAN Name	
$\left[\dfrac{\partial r_{OF}}{\partial \zeta_H}\right]$	=	$\begin{bmatrix} - , & PXFPTB, & PXFPSB \\ PYFPPB, & - , & PYFPSB \\ - , & - , & - \end{bmatrix}$	(1-13)
$\left[\dfrac{\partial \zeta_{OF}}{\partial \zeta_H}\right]$	=	$\begin{bmatrix} PHFPHS, & PHFTHB, & PHFPSB \\ - , & THFTHB, & THFPSB \\ PSFPHB, & PSFTHB, & PSFPSB \end{bmatrix}$	(1-14)
$\left[\dfrac{\partial \zeta_{SP}}{\partial \zeta_H}\right]$	=	$\begin{bmatrix} PFGFB, & PFGTB, & PFGSIB \\ - , & PTGTB, & PTGSIB \\ PSIGFB, & PSIGTB, & PSIGSB \end{bmatrix}$	(1-15)

Rotor (Engine) Rotation

$\dfrac{\partial \phi_{Fn}}{\partial \psi_R}$	=	PFSI(I)	(1-16)

TABLE 1-4. MOTION ARRAY FOLDOVER			
	Array Contents		
COL.	YDD	YD	Y
21	$\ddot{X}_H$	$\dot{u}_H$	u_H
22	$\ddot{Y}_H$	$\dot{v}_H$	v_H
23	$\ddot{Z}_H$	$\dot{w}_H$	w_H
24	$\dot{p}_H$	$\dot{p}_H$	p_H
25	$\dot{q}_H$	$\dot{q}_H$	q_H
26	$\dot{r}_H$	$\dot{r}_H$	r_H
27	$\ddot{\phi}_S$ = ZDD(3)	$\dot{\phi}_E$	ϕ_E
28	$\ddot{\theta}_S$ = ZDD(4)	$\dot{\theta}_E$	θ_E
29	-	$\dot{\psi}_E$	ψ_E
30	-	-	-

for the AH-56A Cheyenne. However any set of tables can be inserted so long as the call argument and table arrangement are correct.

AERO references the blade data stored in block data sets CLATM, CDATM, CLAT, CDAT, CMAM, CMA. These block data sets are entered with the interpolation routines XTRP1, XTRP2 and XTRP3 depending on whether 1, 2 or 3 parameters are being interpolated.

The subroutine call argument is as follows:

Input:

XN Normalized blade span location from 0 to 1.

MACH Local section Mach number.

ALFAR Section angle of attack, rad.

ICMBL Blade pitching moment coefficient flag. This element is also referred to as IBLADE in the calling routines, and sets the trailing-edge configuration for AH-56A blades.

DCMR1 A delta pitching moment coefficient to be added for IBLADE = 3.

Output:

CL   Blade section coefficient of lift

CD   Blade section coefficient of drag

CM   Blade section coefficient of moment

1.3.3 BIRD1

The subroutine BIRD1 has the entry points BIRD1, PBIRD, ABIRD, BBIRD and COR. The code by in large computes and integrates the isolated control gyro equations of Volume I, Section 6.11.

Entry BIRD1 computes the isolated gyro rotating and nonrotating inertias. The ZDD, ZD, Z array is zeroed. The array grouping contains the shaft bending and gyro degrees of freedom. Shaft bending accelerations are computed in ACCEL and integrated within the ZDD array. The gyro equations are developed totally within the ZDD context. A summary of the array is given in Table 1-5.

The entry PBIRD computes the isolated control gyro cyclic actuators time constants. This entry also equivalences the shaft bending accelerations to ZDD format. Adams-Bashforth, open form integration for the ZDD, ZD, Z sets completes PBIRD.

TABLE 1-5. AUXILIARY STATE VARIABLE NOTATION

Variable	Coding
$\ddot{\phi}_G$	ZDD(1)
$\dot{\phi}_G$	ZD(1)
ϕ_G	Z(1)
$\ddot{\theta}_G$	ZDD(2)
$\dot{\theta}_G$	ZD(2)
θ_G	Z(2)
$\ddot{\phi}_S$	ZDD(3)
$\dot{\phi}_S$	ZD(3)
ϕ_S	Z(3)
$\ddot{\theta}_S$	ZDD(4)
$\dot{\theta}_S$	ZD(4)
θ_S	Z(4)

The control flap feedback of Volume I, Section 6.11.4 is coded in entry ABIRD. This code is directly identifiable with the symbols in the text except for GLFEED, GMFEED, the roll and pitch feedback moment components respectively.

The final isolated gyro equations of Volume I, Section 6.11.3 are assembled in the entry BBIRD. This coding can be traced from FKDD = $\ddot{\phi}_G$ and FDDD = $\ddot{\theta}_G$. Entry COR does the bookkeeping for the values of old accelerations and velocities required by the integration scheme. The term NZ is the ZDD, etc., variable size. It is 2 for cases without shaft bending and 4 with.

1.3.4 BMOVE

BMOVE is a bookkeeping subroutine. The prime function is to update the blade bending modes V(J, (1, 2, 3), I) from the YDD, YD, Y arrays. The index J is the mode number (1 to 3). The inner index (1, 2, 3) is for position, velocity, acceleration respectively. The last index, I, is the blade number. The array PDD, PD, P corresponds to YDD, YD, Y for the fourth mode per blade. The index of the "P" arrays is 1 to 4, which is equated to 4, 8, 12 and 16 of the "Y" array terms.

A special version of the "P" arrays uses only information from "Y" array from blade 4. This data is distributed to the "P" locations to form a reactionless pitch horn bending mode.

1.3.5 BSCALE

This subroutine figures an appropriate plot scale factor for the plotted variables to give values of 2, 5 or 10 per line of plot output.

1.3.6 CMLOOK

CMLOOK is the executive subroutine for the seven table lookup scheme moment data acquisition. This subroutine calls the interpolation routine XTRP which operates on the moment data sets T2CM, T1SCM and T1CM. The moment data selection is developed in Section 4.1 below and Volume III, Section 3.3.7.3.

1.3.7 CNTROL

The subroutine CNTROL sets the command control positions in FLY. It consists of the entries CNTROL, APCNTL, PICNTL. Entry CNTROL equates input command time steps to RA inputs and initializes constants used in the subroutine. The entry APCNTL in conjunction with the subroutine PILOTA for a profile follower autopilot. Insufficient information is available to document this section, and it is currently not considered operational. Command cyclic stick, main rotor and tail rotor collectives are computed in entry PICNTL. The input set of position vs. time (20 points) is interpolated for the computation time point. A set of stability augmentation systems are

meshed with these calculations. These devices are noted in the code and diagrammed in Volume III, Section 3.3.4.2.

1.3.8 COULOM

Coulomb friction is calculated by the subroutine COULOM. COULOM is used for swashplate and feather bearing friction as explained in Volume I, Section 6.10 and Figure 6-3.

1.3.9 DERIV

This subroutine codes the equations of Volume I, Section 5.5.1 at entry DERIV and the equations of Volume I, Section 5.5.2 at entry DERIVF. In DERIV the earth Euler angles are THETE (θ_E) and PHIE (ϕ_E). The hub axis accelerations without gravity are UHD, VHD, WHD. These terms correspond to:

$$\begin{Bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{Bmatrix}_H \qquad (1\text{-}17)$$

The earth angle Euler rates are computed as PHIDE, THETDE, PSIDE.

Entry DERIVF computes the fuselage acceleration without gravity (UFD, VFD, WFD) and the fuselage velocity (UF, VF, WF). The gravity vector in fuselage coordinates is GFX, GFY, GFZ. The shaft bending angles ϕ_S, θ_S are coded as PHIS, THTS.

1.3.10 DWASH

This subroutine is a set of numerical first-order time lags applied primarily to main rotor and tail rotor downwash terms. Derivatives are also calculated from time step increments in the downwash components and the respective time constants. The subject is developed in Volume I, Section 7.2.2.4. The main rotor downwash terms are WIMR, PIMR, QIMR. These elements correspond to w_{iMR}, p_{iMR}, q_{iMR}. The derivative counterparts are WIMRD, PIMRD, QIMRD. The tail rotor downwash is WITR.

The tail rotor flapping dynamics are handled in the same manner as the quasi-static pitch horn bending in Volume I, Section 6.6.6. The period of oscillation of the true dynamics is replaced by a first-order lag with a time constant equal to the period. The tail rotor flapping is coded as A1TR.

1.3.11 ETORQ1

ETORQ1 computes the engine model equations of Volume I, Section 6.12.2. The first entry ETORQ1 initializes the gas generator speed storage, NGPRM, NG. The maximum available torque, MZZEDX, is calculated from the maximum horsepower, ENGHPX and nominal rotation speed, O.

The equations are coded in entry ETORQ. $\ddot{\Psi}_{GEN}$ is coded by noting that the acceleration is the difference of velocities between time points divided by the time increment DT. The velocity here is the rotational speed.

$$\dot{\Psi}_{ENG} = NGPRM$$

The engine perturbation torque equation is coded as follows:

$$ENDMZZ = M_{XA_{ENG}}$$

$$MZZTRM = M_{XA_{ENG,\ TRIM}}$$

$$PQENG = \partial M_{ENG}/\partial \dot{\Psi}_{GEN}$$

$$PQEOM = \partial M_{ENG}/\partial \dot{\Psi}_{ENG}$$

Limiters are provided to prevent the engine supplied torque, ENDMZZ, from being negative, or exceeding the maximum available torque, MZZEDX.

1.3.12 FLY

FLY is primarily an executive and outputting subroutine. MAIN calls FLY when TRIM is complete and this subroutine controls the program until the maneuver is complete, at which time control is handed back to MAIN for the next case. The calling sequence in FLY is given in Figure 1-2. The diagram gives a brief description of the major functions of FLY and the subroutine it calls. Each entry into each subroutine is enclosed by a separate box. Each box is headed by the entry name with the subroutine name following in parenthesis.

FLY starts by initializing itself and calling the initialization entries CONTROL and PILOTI. For the first time point only, the program then jumps over a section related to advancing time for computation which need not be performed at zero maneuver time. This section includes calls to PRED, IGYRO, DERIV, DERIVF, BMOVE, PHORN, TO , ETORQ, DWASH, APCNTL and PICNTL.

The reactionless inplane excitation twang, the advancing of time and azimuth, the updating of spatial angles and geometry, and the updating of downwash save variables are also bypassed for the first time frame.

Next, the program proceeds to update the collective and cyclic main rotor angles as function of the swashplate motions. The swashplate motions, in turn, are determined either directly from the stick or from the swashplate control actuators. Then another series of subroutines are called; LOADS, ACCEL, DERIV, CORECT, BMOVE, ABIRD and COR. Next, an exit test is made for excessive rotor loads or the end of the maneuver. All the rest of the program is devoted to collecting plot data on an external storage device and in tabulating output data. At almost the end of the subroutine, there is a section for initialization, if time histories to an expanded time scale are desired, for an extra half second following the normal time histories. Every time point is plotted for the expanded plots, whereas normally a number of time points are skipped for plotting in the interest of keeping the plot length reasonable.

The definitions of input quantities equivalenced to the input RA can be found in Volume III, Section 3.2. The definitions of plot parameters are given in the beginning of subroutine RCPLOT, and the definitions of tabulated values may be found in Volume III, Section 3.3.5.2. The definitions of key variables from the remaining FORTRAN variables follow:

AZM - number of time points during normal or expanded time histories

AZIMUTH - number of time points in FLY

TIME - time in FLY

PTIME - plot time

PDATA - time history parameters

JSTEP - time point counter for ZDD and ZD integration

KSTEP - time point counter for YDD and YD integration for the blade degrees of freedom

LSTEP - time point counter for integration of the remaining YDD and YD variables

IB - number of blades (4 presently)

NVAR - size of generalized mass matrix

SCALE, TSCLE - revolutions and seconds per inch of plot paper

NSAVE - number of time points to next plot point

NPTS - number of points plotted

IPTS - time point counter for plot points

NFREQ - flags expanded time histories.

1.3.13 HARM1

The subroutine HARM1 harmonically analyses selected parameters during extra revolutions added to the TRIM process. Seven harmonics are analyzed, the first being the "0P" or mean value. The formulation is given in Volume III, Section 3.3.6. HARM1 initializes the sine and cosine for the incremental azimuth angle in each harmonic.

The entry HARM evaluates the integrals required in the coefficient definitions. This entry is used every integration time step during the last TRIM revolutions. At entry HARM2, the final coefficients are assembled, the vector form of the analysis is computed, and the harmonic analysis printout is performed. HARM2 also adds labels to the tabulation.

FBSO and FBCO compile the sine and cosine component of each parameter. PHA and AMPL are the vector phase and magnitude representations. SB and CB denote the sine and cosine of the harmonic signal. HACYC is the number of rotor revolutions to be analyzed, usually one.

1.3.14 IGYRO

The purpose of subroutine IGYRO is to provide the capability to subdivide the basic integration step size when applied to the gyro degrees of freedom. The relationship of interest is:

$$dt_{GYRO} = dt/GINT \tag{1-18}$$

Where GINT is an input quantity RA(61) and GINT ≥ 1.

Note that upon return to subroutine FLY, the gyro variables will have been integrated to values corresponding to a time of t + dt.

Although the gyro and flexible shaft degrees of freedom are integrated in the common routine BIRD1, the flexible shaft and subinterval integration step options are not compatible. This is because the gyro degrees of freedom are explicitly solved equations, and therefore, do not depend on the mass matrix operations. Thus the degrees of freedom are not affected by the step size change. Such is not the case with the flexible shaft degrees of freedom which operate through the normal channels. Thus they are directly tied to the mass matrix calculation timing.

1.3.15 INTG

Subroutine INTG is the system integration routine. The integration algorithm used is the four-point Adams-Bashforth open formula

$$y_{n+1} = y_n + \frac{dt}{24}\left[55\dot{y}_n - 59\dot{y}_{n-1} + 37\dot{y}_{n-2} - 9\dot{y}_{n-3}\right] \qquad (1\text{-}19)$$

The subscript n identifies the present time point, and n+1, n-1, n-2 and n-3 neighboring time points newer and older than n. dt is the increment between time points.

Multipoint formulas such as this require companion starter formulas to accumulate back values. The one used in REXOR is the simple Euler formula

$$y_{n+1} = y_n + dt\ \dot{y}_n \qquad (1\text{-}20)$$

This subprogram has three entry points. INTG is the routine initialization entry. Old values of the velocities and accelerations, YD1, YD2, YD3, YDD1, YDD2, YDD3 are zeroed here. Entry PRED evaluates the appropriate integration formulas and advances time.

Entry CORECT performs bookkeeping functions. Back value arrays are shifted to prepare for another integration step. Note that programming is provided to make the first time point in FLY be the same as the last point in TRIM. This is done by back stepping the integration one interval at the end of TRIM so that the first operation in FLY will bring the integration up to date.

Since the integrators are not restarted from the changeover from TRIM to FLY an anomaly can occur. If the integration step sizes for the two modes are different, then the results for the first few points into FLY are not strictly correct until the old integrators are filled with FLY generated values.

1.3.16 LOADS1

The entry point LOADS1 performs a number of initialization and bookkeeping operations. The fuselage lift, drag, moment table argument (ALFA) is converted to radians and a number of storage locations are zeroed out. Also tail rotor aerodynamic coefficients are precomputed.

Main rotor coefficients are precomputed as the first item of entry LOADS. An array of main rotor aerodynamic loads in rotating coordinates are computed in the vector FR. FR is built from the F array from sweep. The second index is blade number. Examples of the terms are vertical load, FR(9), roll moment referenced to blade #1, FR(10), and pitch moment referenced to blade #1, FR(11).

The rotating components are resolved to nonrotating components (FMR) by the Euler rotation Ψ_R. The terms SCY and CCY are the sine and cosine values of Ψ_R. These loads are used in ACCEL to build up the generalized forces as well as main rotor induced velocity calculations.

The new values of w_{iMR} (WIMRN), p_{iMR} (PIMRN) and q_{iMR} (QIMRN) are computed as given in Volume I, Section 7.2.2.2. Next the tail rotor loads are partially calculated as given in Volume I, Section 7.5.1.

Wake angle logic determines if rearward flight or hovering conditions exist to avoid obtaining an improper answer from the use of the arctangent function. Using the evaluated wake angle (A1), the wake angle tables are interpolated for the interference factor. Note the FXTN interference table contains both fuselage and tail location factors. For I = 1 the table is used to get the fuselage factor FX. For I = 2, the table produces the tail wake factor which is used in the temporary computation register TNBODY. Vertical velocity terms WBODY and WBODYD are then computed using this interference data.

An array of derivative fuselage (non main rotor) aerodynamic loads are computed as FNW and are directly identified with Volume I, Section 7.4.1. Static data are added to these terms. The C_L, C_D, and C_M are interpolated as a function of local angle of attack ALFAB and input data ALFA(I). The combined FNW array is resolved to fuselage axis as per Volume I, Section 7.4.1 in array FN. The tail rotor loads, FTR, and propeller table lookup, FP, follow Volume I, Sections 7.5.2 and 7.6.1. The final operation is to sum FN, FTR, and FP, and convert to the actual air density. This final summation is stored as QLOADS for use in ACCEL.

1.3.17 LSTDAT

This subprogram is called once at the outset of a computer run and performs two major functions. One, it provides a card image listing of the data deck just as it was submitted. This provides an exact record of the data for the given run. Second, LSTDAT prepares a working data set by transferring the data to an I/O unit NUNIT. NUNIT is currently assigned the number 3. See Volume III, Section 6.

1.3.18 MAIN

As the name implies, this routine controls the REXOR computation sequence. The first function is to initialize the problem through internal operations and calling of the initializing entries of the subroutines LOADS1, SWEEP1, ACCEL1, INTG, TORS1, BIRD1, BMOVE, ETORQ1. Control then passes to TRIM, which in fact is an executive routine. On completion of a successful trim or time limit, control transfers to FLY. If a number of input cases are being run, control cycles back to label 10 for additional runs.

1.3.19 MIC 26

Within REXOR, the equations of motion are stated

$$\{\ddot{q}\} = \{\Delta\ddot{q}\} + \{\ddot{q}_{EST}\} \tag{1-21}$$

where

$$\{\Delta\ddot{q}\} = [M]^{-1}\{\Delta F\} \tag{1-22}$$

M and ΔF are given. $\Delta\ddot{q}$ can be computed by first inverting M, then performing the indicated multiplication. A more efficient method is to solve for the product directly by solving the linear system

$$[M]\{\Delta\ddot{q}\} = \{\Delta F\} \qquad \text{for } \{\Delta\ddot{q}\} \tag{1-23}$$

It is further known that the mass matrix, $[M]$, is positive definite and symmetric. Subprogram MIC26 is a general algorithm for the solution of simultaneous equations of the form

$$[A]\{x\} = \{b\} \tag{1-24}$$

where the coefficient matrix is positive definite, symmetric. The algorithm is a Cholesky decomposition of $[A]$, followed by a forward-backward substitution. The algorithm is presented below.

Cholesky Method for Symmetric, Positive Definite Matrices.

Theorem: Let A be symmetric, positive definite. Then A can be factored in the form

$$LL^T = A \tag{1-25}$$

where L is a lower triangular matrix (i.e., $L = (\ell_{ij})$ where $\ell_{ij} = 0$ for $j > i$)

Cholesky Method: Let A be n x n, symmetric, positive definite

$$A = (a_{ij}) \quad , \quad a_{ij} = a_{ji} \tag{1-26}$$

Assume A is factorable

$$A = LU \tag{1-27}$$

Then,

$$a_{ij} = \sum_{k=1}^{n} \ell_{ij} u_{kj} \tag{1-28}$$

If

$$U = L^T \quad , \quad u_{kj} = \ell_{jk} \tag{1-29}$$

Then

$$a_{ij} = \sum_{k=1}^{n} \ell_{ik} \ell_{jk} \qquad i = 1, n; \; j = 1, n \tag{1-30}$$

But L is lower triangular, which implies $\ell_{ik} = 0$ for $k > i$. Therefore,

$$a_{ij} = \sum_{k=1}^{i} \ell_{ik} \ell_{jk} \qquad i = 1, n; \; j = i, n \tag{1-31}$$

Equation (1-31) forms the basis of the decomposition. The elements of L are found as follows.

$$\ell_{11} = \sqrt{a_{11}} \tag{1-32}$$

Also

$$a_{1j} = \ell_{11}\,\ell_{j1}$$

leads to:

$$\ell_{j1} = a_{1j}/\ell_{11} \quad , \qquad j = 2, n \tag{1-33}$$

and

$a_{ii} = \sum_{k=1}^{i} \ell_{ik}^{\,2} = \sum_{k=1}^{i-1} \ell_{ik}^{\,2} + \ell_{ii}^{\,2}$ for $i = 2, n$ can be solved for ℓ_{ii}.

$\therefore$

$$\ell_{ii} = \sqrt{a_{ii} - \sum_{k=1}^{i-1} \ell_{ik}^{\,2}} \quad . \tag{1-34}$$

Finally,

$$a_{ij} = \sum_{k=1}^{i-1} \ell_{ik}\,\ell_{jk} + \ell_{ii}\,\ell_{ji} \quad , \qquad i = 2, n \tag{1-35}$$

giving:

$$\ell_{ji} = \left(a_{ij} - \sum_{k=1}^{i-1} \ell_{ik}\,\ell_{jk}\right) \Big/ \ell_{ii} \tag{1-36}$$

With the decomposition of A, the system (1-24) can be solved as follows. Substitute $A = LL^T$ into (2). $LL^Tx = b$

and

$$g = L^T x \tag{1-37}$$

Solve $Lg = b$ by forward substitution. Namely,

$$g_1 = b_1/\ell_{11} \tag{1-38}$$

and

$$g_i = \left(b_i - \sum_{k=1}^{i-1} \ell_{ik}\, g_k\right)\Big/\ell_{ii} \quad , \qquad i = 2, n \tag{1-39}$$

Finally, find x from (1-37) by backward substitution.

$$x_n = g_n/\ell_{nn} \tag{1-40}$$

$$x_j = \left(g_j - \sum_{k=j+1}^{n} \ell_{kj}\, x_k\right)\Big/\ell_{jj} \tag{1-41}$$

Equations (1-32) through (1-36) and (1-38) through (1-41) form the algorithm.

The arguments in the subprogram calling sequence are

MIC26 (A, B, N, M, L)

where A is the coefficient matrix of a maximum dimension M x M. A submatrix problem of size N x N can be solved. B is the right-hand matrix of

dimension N x L on entry and the solution matrix on exit. The algorithm assumes A is symmetric and only operates on the lower triangular portion. A is destroyed on exit.

An error exit can occur from the routine. While forming the elements as given by equation (1-35), the argument of the square root function is tested. If

$$a_{ii} - \sum_{k=1}^{i-1} \ell_{ik}^{2} < 0 \tag{1-42}$$

then the procedure is terminated. This is interpreted as an indication of failure to be positive-definite. A normal exit from the routine is indicated by:

$$A_{11} = 0 \tag{1-43}$$

An error exit is indicated by:

$$A_{11} = j \tag{1-44}$$

Where j is the row number at failure.

The subprogram MIC26 is computed in double precision on IBM hardware. This means the matrices A and B are double precision. The CDC version is single precision. See Volume III, Section 6.

1.3.20 MINVR

This subprogram will compute the inverse of a matrix by Gaussean Elimination with pivoting. The inversion is performed in single precision and the matrix dimensions have been specialized to 6 by 6. The calling sequence arguments are MINVR (A, N, B, IER, W)

where

A - input matrix of order N x N N - 6.

B - output matrix A^{-1}

W - work array of size 6 by 6

IER = error indicator

0 - normal

1 - pivot element zero. (no inversion)

MINVR is called only once from TRIM and only if one of the unsupported trim options is activated. Its sole purpose is to provide a constant sensitivity matrix for a Newton-Raphson type of iterative equation. Given A, find $B = A^{-1}$ to be used in an equation of the form

$$x_{n+1} = x_n - B \cdot f \qquad (1\text{-}45)$$

where x is a control vector and f is a trim error vector.

1.3.21 MPRNT

MPRNT is a generalized matrix formatted print routine. It is called by subprogram ACCEL to provide a print of the mass matrix. The printing is optional. If activated, via input, the mass matrix is printed once at the beginning of TRIM and FLY.

1.3.22 PDATE

Subprogram is a dummy date routine which is to be supplied by the installation of interest. The calling routine displays the date to be presented as a 1 word, 8 character literal.

```
CALL PDATE (NDATE)
```

The argument NDATE is typed as REAL *8 for IBM software. The image is expected to be of the form

MO - DA - YR .

The CDC counterpart is typed real and is also of the form,

MO - DA - YR ,

giving eight characters left adjusted.

1.3.23 PHORN

This subroutine solves the isolated pitch horn bending equation of Volume I, Section 6.6.6. TPH is τ_{PH}. The term TFA corresponds to blade feathering moment M_{Fn}. DPF represents $\phi_{Fn,PH}$, and DPFD gives $\dot{\phi}_{Fn,PH}$.

1.3.24 PRINT1

Subprogram PRINT1 has multiple entry points all called from subprogram READIN. Entry PRINT1 presents a formatted printing of the master data deck. Each input is identified by listing its address, program name, and value. Tabular information is presented as such with some grouping for easy identification. Entry PRINT gives case data as an exception report. Case data which is different in value from the master data value is presented.

1.3.25 PROP

PROP is a data bank of propeller tables for the AH-56A. This data is used by the subroutine/entry LOADS1/LOADS via the bivariant interpolation XTRP2. The first grouping of data PROP1 contains C_T information as a function of blade angle, β, and advance ratio, J. The second grouping, PROP2 contains similar information for C_P.

1.3.26 RCPLOT

This subprogram performs all the CALCOMP plotting. The coding has been arranged to give optimal results when used with the 12-inch drum CALCOMP machines. Other units may require some reprogramming to achieve useful results. The routine performs as described in Volume III, Section 3.3.5. It is called optionally from TRIM, for trim and harmonic analysis plots, and from FLY for maneuver time histories. It will also optionally prepare a data set of signals for transform analysis. The calling sequence is as follows:

RCPLOT (NVAR, NVEC, NPTS, CASE, PLTINC)

where:

NVAR - number of parameters to be plotted.

NVEC - parameter code table.

NPTS - number of points to plot.

CASE - case number.

PLTINC - time between data points.

NVEC = NVEC1 = RA(301) through RA(340) in TRIM, or NVEC = NVEC2 = RA(1801) through RA(1860) in FLY. Up to 90 parameters can be plotted, however numbers greater than 60 fold over on a modulus 60 basis.

Some input factors and controls are transmitted through the COMMON statements. The scaling is done by the subprogram BSCALE, if automatic scaling is used. SVEC = RA(1851) through RA(1900) sets the scale factors in FLY.

1.3.27 READIN

This subprogram processes the input data, building cases as defined by the control cards. The master data configuration is preserved in array RAS. The working case configuration is defined in array RA. READIN senses the end of a computer run, terminates the plot data file and exits execution.

1.3.28 STALL

STALL computes the elements of dynamic stall given in Volume I, Section 7.2.3.4. The subroutine is called from SWEEP, and is operative with the fast aero lookup scheme (Volume I, Section 7.2.4.3 and Section 4.2 of this volume). The partial derivative ($\partial C_L/\partial \alpha$) is calculated by two calls to AERO with angles of attack of 0 and 0.01 radian. The CL differences are multiplied by 100 and termed DCLDAO. The dynamic stall delay, γ, is computed as TEMP with Mach limitations of 0.25 and 0.6. The reference angle of attack α_{REF} is then calculated as AD.

A logic sequence given in Volume I, Section 7.2.3.4.1 is used to select the proper ($\partial C_L/\partial \alpha$) so that the static lift slope line is not exceeded. The value selected then occupies TEMP. CLR is the completed lift slope value.

The dynamic stall moment calculations are produced simultaneously with the above operations, and in accord with Volume I, Section 7.2.3.4.2. The factor K is FACTM and α_{REF} is ADM. The final moment coefficient is CMR.

1.3.29 SWEEP1

SWEEP is the key routine to the REXOR program. Elements of Volume I, Sections 5.5.5 and 6.6 are computed here. The blade equations of motion ingredients are computed for an azimuth step for each blade and radial station.

SWEEP1 has the entries SWEEP1 and SWEEP. A large amount of information is equivalenced from input RA set in SWEEP1 as well as out to names used in other routines. The RA names can be matched against the input set

description of Volume III, Section 3.2. If the fast aero option is specified the five-point input thickness and design lift coefficient points are interpolated to the blade radial stations used. The thickness values are TCN(K) and the lift coefficients are CLN(K).

Radial stations are set for output functions and for use in other subroutines. These are NTH1, NTH2, NSTAF. The first two are stations to read out dynamic torsion. The third is the point to read out effective sweep and droop. Program logic outputs data at the closest blade station. Blade mass, BLMASS, and rotor polar inertia, IZZR, are precomputed at this point. The factor DSS2(K) is the coefficient string for trapezoidal integration.

Coordinate transformation parts and feather axis data are next precomputed. BO is β_o, GAM is γ, BF is β_{FA}, PHIREF is ϕ_{REF}. Transformations calculated are

$$\left[T_{46}\right] = \left[T_{\beta_{FA}}\right]^T \left[T_{\phi_{REF}}\right]^T \left[T_{\beta_{FA}}\right] \tag{1-46}$$

$$\left[T_{47}\right] = \left[T_{\tau_o}\right]^T \left[T_{\gamma}\right]^T \tag{1-47}$$

and partially

$$\left[T_{48}\right] = \left[T_{\beta_O}\right]^T \left[T_{\phi_T}\right]^T \tag{1-48}$$

The elements XRI, ZRI, XRO, ZRO are the inboard and outboard tension-torsion attach point locations.

The entry SWEEP is called from LOADS for each azimuth step. First the hub set airflow angles are computed per Figure 5-4 of Volume I. A2 is α_2 and sine, cosine components of ψ_W are SPSW and CPSW. Main rotor ground effect coefficient f_{iMR} is FH1.

Inboard and outboard feather bearing displacements, velocities, and accelerations are then determined. The modal coefficients used are pre-interpolated to the bearing locations.

These coefficients are defined as:

FBL1I, first inplane made

FBL1F, first flap mode

FBL2F, second flap mode

With the argument:

$$\left(\begin{array}{c} 1 = \text{inplane deflection} \\ \text{or} \\ 2 = \text{flapping deflection} \end{array} \quad , \quad \begin{array}{c} 1 = \text{inboard location} \\ \\ 2 = \text{outboard location} \end{array} \right)$$

The modal variable is coded as:

$$V \left(\begin{array}{c} \text{mode number} \\ \\ 1, 2 \text{ or } 3 \end{array} \; , \; \begin{array}{l} \text{type} \\ \\ 1 = \text{displacement} \\ 2 = \text{velocity} \\ 3 = \text{acceleration} \end{array} \; , \; \begin{array}{c} \text{I for} \\ \\ \text{blade} \\ \text{number} \end{array} \right)$$

Using the data calculated above, the angles Y'_{FA} (YPFA) and Z'_{FA} (ZPFA) as well as associated time derivatives are programmed. Next, the terms CPSI and SPSI set up the cosine and sine of Ψ_R for each blade.

The remaining elements prior to integrating (sweeping) out the blade set up needed transformations and partial derivatives.

Key items are:

CPPW, SPPW — relative wind angle resolved into BLn set

VKOROC chordwise velocity with ground effect

G_1, G_2, G_3 hub set acceleration resolved to BLn set

XT1,..., ZT3 angular acceleration cross product terms

ANGR(1), ANGR(2), ANGRD(1), ANGRD(2) — BLn set roll and pitch rate and acceleration

THF true, total feather command, and numerous partial derivatives:

PFTHO $= \partial\phi_F/\partial\theta_C$

PFA1S $= \partial\phi_F/\partial A_{1S}$

PFB1S $= \partial\phi_F/\partial B_{1S}$

PFHG(I) $= \partial\phi_F/\partial Z_G$

PFGK(I) $= \partial\phi_F/\partial\phi_G$

PFGD(I) $= \partial\phi_F/\partial\theta_G$

PFBLFB $= \partial\phi_{BLE}/\partial\phi_H$

PFBLF $= \partial\phi_{BLE}/\partial\phi_F$

PFBLTB $= \partial\phi_{BLE}/\partial\theta_H$

PFSI(I) $= \partial\phi_F/\partial\psi_R$

$$\begin{array}{l} \text{PXRXB(I)} = \\ \text{PYRXB(I)} = \\ \text{PZRZB(I)} = \\ \text{PYRYB(I)} = \\ \text{PXRYB(I)} = \end{array} \left\{ \begin{array}{l} \partial X_{BLn}/\partial_X \\ \partial Y_{BLn}/\partial_X \\ \partial Z_{BLn}/\partial_Z \\ \partial Y_{BLn}/\partial_Y \\ \partial X_{BLn}/\partial_Y \end{array} \right\}_H$$

DELPHI $= \Delta\phi_F$

YPV1 $= \partial Y'_{FA}/\partial A_1$

. .

. .

. .

ZPV3 $= \partial Z'_{FA}/\partial A_3$

TPV1 $= \partial\phi_F/\partial A_1$

Using the subroutine XTERMO and multiple entry points, these transformations are calculated.

$$\left[T2\right] = \left[T_{\Delta\phi_F}\right] \left[T_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right] \tag{1-49}$$

$$\left[T3\right] = \left[\dot{T}_{\Delta\phi_F}\right] \left[T_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right] \tag{1-50}$$

$$\left[T4\right] = \left[T_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[T_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right] \tag{1-51}$$

$$\left[T5\right] = \left[T_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \tag{1-52}$$

$$\begin{aligned}\left[T10\right] = {} & \left[\dot{T}_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[T_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right] \\ & + \left[T_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[T_{Y'_{FA}}\right] \left[\dot{T}_{Z'_{FA}}\right]\end{aligned} \tag{1-53}$$

$$\left[T17\right] = \left[T_{Z'_{FA}}\right]^T \left[\dot{T}_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[T_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right]$$

$$+ \left[T_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[\dot{T}_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right] \qquad (1\text{-}54)$$

$$\left[T20\right] = \left[T_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \left[\dot{T}_{\Delta\phi_F}\right]^T \left[T_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right] \qquad (1\text{-}55)$$

$$\left[T25\right] = \left[\dot{T}_{Z'_{FA}}\right]^T \left[\dot{T}_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[T_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right]$$

$$+ \left[\dot{T}_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[\dot{T}_{Y'_{FA}}\right] \left[T_{Z'_{FA}}\right]$$

$$+ \left[T_{Z'_{FA}}\right]^T \left[\dot{T}_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[T_{Y'_{FA}}\right] \left[\dot{T}_{Z'_{FA}}\right]$$

$$+ \left[T_{Z'_{FA}}\right]^T \left[T_{Y'_{FA}}\right]^T \left[T_{\Delta\phi_F}\right]^T \left[\dot{T}_{Y'_{FA}}\right] \left[\dot{T}_{Z'_{FA}}\right] \qquad (1\text{-}56)$$

[T30], [T36], [T37], [T39], [T33] are partial elements of double dot transformation $\ddot{r}_{BLn}$ from $\ddot{r}_{BLE}$ data. [T42] is the transform elements less

translation. The preamble concludes by zeroing a number of storage locations.

The majority of the calculations within SWEEP are governed by two FORTRAN DO loop indicies, I and K. I is the blade index and K is the station index. Once the preamble calculations for each blade are determined, the blade spatial integration loop, controlled by index K, begins.

First, the bending acceleration array is built as

$$\begin{Bmatrix} VEC16 \\ VEC17 \\ VEC18 \end{Bmatrix} = \begin{Bmatrix} VEC4(1) \\ VEC4(2) \\ VEC4(3) \end{Bmatrix} = \begin{Bmatrix} 0 \\ \ddot{Y}_{BLE} \\ \ddot{Z}_{BLE} \end{Bmatrix}_{BEND} \qquad (1\text{-}57)$$

The modal coefficients are coded as BMS1I for first inplane, BMS1F for first flap, and BMS2F for second flap. These variables use the following argument scheme.

$$\left(K = \text{blade station}, \quad \begin{matrix} 1 = \text{Y deflection} \\ 2 = \text{Z deflection} \\ 3 = \text{Y'slope} \\ 4 = \text{Z'slope} \end{matrix} \right)$$

The modal variable V's are used as previously described. PHIT is the instantaneous blade twist, and is used to complete [T48].

Next, the transformation of Volume I, Section 5.5.5 from BLE to BLn axis is developed.

Waypoints are

$$\begin{Bmatrix} XSTAT \\ YSTAT \\ ZSTAT \end{Bmatrix} = \begin{Bmatrix} X_{BLE} \\ Y_{BLE} \\ Z_{BLE} \end{Bmatrix}_{STATIC} \qquad (1\text{-}58)$$

$$\begin{Bmatrix} XBRA \\ YBRA \\ ZBRA \end{Bmatrix} = \begin{Bmatrix} BLAD(1) \\ BLAD(2) \\ BLAD(3) \end{Bmatrix} \qquad (1\text{-}59)$$

$$\begin{Bmatrix} DUMO(1) \\ DUMO(2) \\ DUMO(3) \end{Bmatrix} = \begin{Bmatrix} 0 \\ \dot{Y}_{BLE} \\ \dot{Z}_{BLE} \end{Bmatrix}_{BEND} - \begin{Bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{Bmatrix}_{INBOARD} \qquad (1\text{-}60)$$

$$\begin{Bmatrix} XD \\ YYD \\ ZD \end{Bmatrix} = \begin{Bmatrix} \dot{X}_{BLE} \\ \dot{Y}_{BLE} \\ \dot{Z}_{BLE} \end{Bmatrix}_{BLn} , \quad \begin{Bmatrix} X \\ YY \\ Z \end{Bmatrix} = \begin{Bmatrix} X_{BLE} \\ Y_{BLE} \\ Z_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}61)$$

Likewise for accelerations noting the X values are done later.

$$\begin{Bmatrix} XDD \\ YYDD \\ ZDD \end{Bmatrix} = \begin{Bmatrix} \ddot{X}_{BLE} \\ \ddot{Y}_{BLE} \\ \ddot{Z}_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}62)$$

Similar procedures are followed for the bending slopes. Again noting waypoints:

$$\begin{Bmatrix} VEC10 \\ VEC11 \\ VEC12 \end{Bmatrix} = \begin{Bmatrix} 0 \\ Y'_{BLE} \\ Z'_{BLE} \end{Bmatrix}_{BEND} \qquad (1\text{-}63)$$

$$\begin{Bmatrix} VEC13 \\ VEC14 \\ VEC15 \end{Bmatrix} = \begin{Bmatrix} 0 \\ \dot{Y}'_{BLE} \\ \dot{Z}'_{BLE} \end{Bmatrix}_{BEND} = \begin{Bmatrix} VECT3(1) \\ VECT3(2) \\ VECT3(3) \end{Bmatrix} \qquad (1\text{-}64)$$

$$\begin{Bmatrix} VECT5(1) \\ VECT5(2) \\ VECT5(3) \end{Bmatrix} = \begin{Bmatrix} 0 \\ \ddot{Y}'_{BLE} \\ \ddot{Z}'_{BLE} \end{Bmatrix}_{BEND} \qquad (1\text{-}65)$$

Going through coordinate transformations gives

$$\begin{Bmatrix} - \\ YP \\ ZP \end{Bmatrix} = \begin{Bmatrix} - \\ Y'_{BLE} \\ Z'_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}66)$$

$$\begin{Bmatrix} - \\ YPDI \\ ZPDI \end{Bmatrix} = \begin{Bmatrix} - \\ \dot{Y}'_{BLE} \\ \dot{Z}'_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}67)$$

$$\begin{Bmatrix} - \\ YPDDI \\ ZPDDI \end{Bmatrix} = \begin{Bmatrix} - \\ \ddot{Y}'_{BLE} \\ \ddot{Z}'_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}68)$$

A series of transforms are then constructed. These elements are used to calculate angular transforms. First, the elements of TZB are $\left[T_{Z'_{BEND}}\right]^T$. Other pairs are: TZBI with $\left[T_{Z'_{BEND}}\right]$, TYB with $\left[T_{Y'_{BEND}}\right]$ and TYBI with $\left[T_{Y'_{BEND}}\right]^T$.

Using these formulations leads to

$$\{ANGBL\} = \begin{Bmatrix} p \\ q \\ r \end{Bmatrix}_{BLE} \tag{1-69}$$

and

$$\{ANGBLD\} = \begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix}_{BLE} \tag{1-70}$$

Continuing a previous computation string, some of the required partial derivatives are then formulated.

$$\begin{Bmatrix} YV1 \\ YV2 \\ YV3 \end{Bmatrix} = \left\{ \partial Y_{BLE}/\partial A_{1,2,3} \right\}_{BLn} \tag{1-71}$$

$$\begin{Bmatrix} ZV1 \\ ZV2 \\ ZV3 \end{Bmatrix} = \left\{ \partial Z_{BLE}/\partial A_{1,2,3} \right\}_{BLn} \tag{1-72}$$

$$\begin{Bmatrix} YDPAR1 \\ YDPAR2 \\ YDPAR3 \end{Bmatrix} = \left\{ \partial Y'_{BLE}/\partial A_{1,2,3} \right\}_{BLn} \tag{1-73}$$

$$\begin{Bmatrix} \text{ZDPAR1} \\ \text{ZDPAR2} \\ \text{ZDPAR3} \end{Bmatrix} = \left\{ \partial Z'_{BLE} / \partial A_{1,2,3} \right\}_{BLn} \qquad (1\text{-}74)$$

$$\begin{Bmatrix} W4 \\ W5 \\ W6 \end{Bmatrix} = \begin{Bmatrix} p \\ q \\ r \end{Bmatrix}_{BLE} \qquad (1\text{-}75)$$

$$\begin{Bmatrix} W7 \\ W8 \\ W9 \end{Bmatrix} = \begin{Bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{Bmatrix}_{BLE} \qquad (1\text{-}76)$$

To this point a number of Y and Z components have been developed. Elements to proceed with similar X calculations are done starting after label 320. Members of the procedure are:

SYS	running sum of spline length S	See Section 5.5.5.10 of Volume I
YNAOBL	Y_{ONA}	
YNABLS	running sum of Y_{ONA} in BLn	
YNABLR	increment of Y_{ONA} between K and K-1	
ZNABLS	running sum of Z_{NA} in BLn	
ZNABLR	increment of Z_{NA} between K and K-1	
YNAS	running sum of Y_{NA} in BLn	
YNAR	increment of Y_{NA} between K and K-1	
W	value of X without corrective term	
X	$W - X_{NA} = X_{NA}$ in BLn	

Similar operations then are performed to get $\dot{X}_{NA}$ and $\ddot{X}_{NA}$ These are noted by the D and DD in the notation.

Returning to partial derivative calculations prior to aerodynamic calculations:

$$\left\{ PAA \begin{pmatrix} 1 = A_1 \\ 2 = A_2 \\ 3 = A_3 \end{pmatrix} \begin{pmatrix} 1 = \phi \\ 2 = \Theta \\ 3 = \Psi \end{pmatrix} \right\} = \left\{ \begin{matrix} \partial\phi_{BLE}/\partial A_{mn} \\ \partial\Theta_{BLE}/\partial A_{mn} \\ \partial\Psi_{BLE}/\partial A_{mn} \end{matrix} \right\}_{BLE} \qquad (1\text{-}77)$$

An example is PAA1(2).

$$\begin{Bmatrix} PXBLFB \\ PYBLFB \\ PZBLFB \end{Bmatrix} = \frac{\partial}{\partial\phi_R} \begin{Bmatrix} X_{BLE} \\ Y_{BLE} \\ Z_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}78)$$

$$\begin{Bmatrix} PXBLTB \\ PYBLTB \\ PZBLTB \end{Bmatrix} = \frac{\partial}{\partial\Theta_R} \begin{Bmatrix} X_{BLE} \\ Y_{BLE} \\ Z_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}79)$$

$$\begin{Bmatrix} PXBLSI \\ PYBLSI \\ PZBLSI \end{Bmatrix} = \frac{\partial}{\partial\Psi_R} \begin{Bmatrix} X_{BLE} \\ Y_{BLE} \\ Z_{BLE} \end{Bmatrix}_{BLn} \qquad (1\text{-}80)$$

Now some Z derivatives can be made along the lines used to generate X_{NA}. Output terms are:

$$XV1 = \partial X_{BLE}/\partial A_{1n}$$

$$XV2 = \partial X_{BLE}/\partial A_{2n}$$

$$XV3 = \partial X_{BLE}/\partial A_{3n}$$

At this juncture, sufficient information exists to develop the aerodynamic loading functions and complete the blade calculations of this subroutine. First looking at air velocities:

$$\begin{Bmatrix} UT1 \\ UT2 \\ UP \end{Bmatrix} = \begin{Bmatrix} X \\ Y \text{ air velocities} \\ Z \end{Bmatrix}_{BLn} \tag{1-81}$$

$$\begin{Bmatrix} V2(1) \\ V2(2) \\ V2(3) \end{Bmatrix} = \begin{Bmatrix} X \\ Y \text{ air velocities} \\ Z \end{Bmatrix}_{BLE} \tag{1-82}$$

Note the more traditional usage is equivalenced at this point.

UC - air velocity chordwise

UN - air velocity normal to chord.

From this data the angle-of-attack information and assorted aero terms are computed.

ALFAR - angle of attack

ALFDOT - rate of angle of attack

QC - aerodynamic pressure times chord

RFREQ - reduced frequency

AYAW - spanwise flow angle of attack

Depending on the option selection, the aerodynamic loading comes from calling STALL, AERO or the pair XTRP4, CMLOOK. The first candidate is used for dynamic stall. Dynamic stall uses fast aero (AERO) which, as indicated, may be used without dynamic stall directly from SWEEP. The other loading data source is the 7 table aero lookup. Here the subroutine XTPR4 produces C_L and C_D. C_M data comes from CMLOOK. The resulting aero loadings are:

$$\begin{Bmatrix} FNO \\ FC \\ TX \end{Bmatrix} = \begin{Bmatrix} \text{normal force} \\ \text{chordwise force} \\ \text{torsion moment} \end{Bmatrix}_{BLE} \tag{1-83}$$

The ingredients necessary for the REXOR equations of motion are assembled in the array FI, which is given in Table 1-6. These elements are per

TABLE 1-6. FI LIST IN SWEEP

Element		Use
	FI (1)	$F_X\ \partial X/\partial A_1 + F_Y\ \partial Y/\partial A_1 + F_Z\ \partial Z/\partial A_1 + M_X\ \partial\phi/\partial A_1 + M_Z\ \partial\psi/\partial A_1$
	FI (2)	$F_X\ \partial X/\partial A_2 + F_Y\ \partial Y/\partial A_2 + F_Z\ \partial Z/\partial A_2 + M_X\ \partial\phi/\ A_2 + M_Z\ \partial\psi/\partial A_2$
See $F_{A_{mn}}$ Volume I, section 6.6.4	FI (3)	$F_X\ \partial X/\partial A_3 + F_Y\ \partial Y/\partial A_3 + F_Z\ \partial Z/\partial A_3 + M_X\ \partial\phi/\partial A_3 + M_Z\ \partial\psi/\partial A_3$
	FI (4)	$\left\{ F_{X_{BLE}} \right.$
	FI (5)	$F_{Y_{BLE}}$
	FI (6)	$\left. F_{Z_{BLE}} \right\}_{BL}$
	FI (7)	$\left\{ M_{X_{BLE}} \right.$
	FI (8)	$M_{Y_{BLE}}$
	FI (9)	$\left. M_{Z_{BLE}} \right\}_{BL}$

TABLE 1-6 - Continued

Element		Use
FI(10)	$F_{X_{BLE}}$	
FI(11)	$F_{Y_{BLE}}$	Aerodynamic loading only
FI(12)	$\left. F_{Z_{BLE}} \right\}_{BL}$	
FI(13)	$M_{X_{BLE}}$	
FI(14)	$M_{Y_{BLE}}$	Aerodynamic loading only
FI(15)	$\left. M_{Z_{BLE}} \right\}_{BL}$	
FI(16)	$\left(M_{X_{BLE}}\right)$	Aero only
FI(17)	-	Diagnostics
FI(18)	$M_{X_{BLE}}$	
FI(19)	$M_{\phi_F \phi_F}$	Generalized masses completed in sweep, typical
FI(20)	$M_{\phi_F A_1}$	
FI(21)	$M_{\phi_F A_2}$	

TABLE 1-6 - Continued	
Element	Use
FI(22)	$M_{\phi_F A_3}$
FI(23)	$M_{A_1 A_1}$
FI(24)	$M_{A_1 A_2} = M_{A_2 A_1}$ (Typical)
FI(25)	$M_{A_1 A_3}$
FI(26)	$M_{A_2 A_2}$
FI(27)	$M_{A_2 A_3}$
FI(28)	$M_{A_3 A_3}$
FI(29)	$M_{\psi_R A_1}$
FI(30)	$M_{\psi_R A_2}$
FI(31)	$M_{\psi_R A_3}$
FI(32)	$M_{\psi_R \phi_F}$

TABLE 1-6 - Continued	
Element	Use
FI(33)	$m\ \partial X/\partial A_1 = M_{X_{OBL}}\ A_1$
FI(34)	$m\ \partial X/\partial A_2 = M_{X_{OBL}}\ A_2$
FI(35)	$m\ \partial X/\partial A_3 = M_{X_{OBL}}\ A_3$
FI(36)	$m\ \partial Y/\partial A_1 = M_{Y_{OBL}}\ A_1$
FI(37)	$m\ \partial Y/\partial A_2 = M_{Y_{OBL}}\ A_2$
FI(38)	$m\ \partial Y/\partial A_3 = M_{Y_{OBL}}\ A_3$
FI(39)	$m\ \partial Y/\partial \phi_F = M_{Y_{OBL}}\ \phi_F$
FI(40)	$m\ \partial Z/\partial A_1 = M_{Z_{OBL}}\ A_1$
FI(41)	$m\ \partial Z/\partial A_2 = M_{Z_{OBL}}\ A_2$
FI(42)	$m\ \partial Z/\partial A_3 = M_{Z_{OBL}}\ A_3$
FI(43)	$m\ \partial Z/\partial \phi_{Fn} = M_{Z_{OBL}}\ \phi_F$
FI(44)	$M_{\phi_H A_1}$

TABLE 1-6 - Continued	
Element	Use
FI(45)	$M_{\phi_H A_2}$
FI(46)	$M_{\phi_H A_3}$
FI(47)	$M_{\phi_H \phi_F}$
FI(48)	$M_{\theta_H A_1}$
FI(49)	$M_{\theta_H A_2}$
FI(50)	$M_{\theta_H A_3}$
FI(51)	$M_{\theta_H \phi_F}$
FI(52)	$\left(M_{\phi_H \psi_R}\right)_{BL}$
FI(53)	$\left(M_{\theta_H \psi_R}\right)_{BL}$
FI(54)	$m *(-X) = M_{Z_{OBL} \theta_{BL}}$
FI(55)	$m * Y = M_{X_{OBL} \psi_{BL}}$
FI(56)	$m *(-Z) = M_{Y_{OBL} \phi_{BL}}$

TABLE 1-6 - Continued

Element	Use
FI(57), FI(58), FI(59)	Similar to FI (1), (2), (3) but aero only (diagnostics)
FI(60)	$M_{\beta_{PH} A_1}$
FI(61)	$M_{\beta_{PH} A_2}$
FI(62)	$M_{\beta_{PH} A_3}$ Uncoupled dynamic
FI(63)	$M_{\beta_{PH} \phi_F}$ Torsion option
FI(64)	$M_{\beta_{PH} \beta_{PH}}$
FI(65)	$F_{\beta_{PH}}$ less - $K_{\beta_{PH} \beta_{PH}}$ term

NOTES: 1. FI's summed over blade and stored as: F (1-65), (n = 1 - 4)

2. FI(66) gives remaining part of

$$F_{\beta_{PH}} \text{ as } \left(\frac{\partial \phi_F}{\partial \beta_{PH}} \right)^2 \frac{1}{GJ}.$$

Formulation not used in ACCEL.

radial station. The array F(J, I) stores the results of trapezoid integration of FI. The index J coincides with the meaning of the elements of FI. I is the blade number. The F array appears in LOADS and ACCEL.

1.3.30 TRIM

The subroutine TRIM performs the function of producing an initial set of conditions for the equations of motion from the user supplied set of flight conditions. TRIM works in a number of different modes depending on the type of flight condition, such as free flight or fixed rotor, and the vehicle configuration itself. Particular items are the arrangement of the lifting surfaces, and the control system configuration. The TRIM options to accommodate the different required modes are by in large controlled by CORAF = RA(42).

TRIM operates as a set of servo loops which through successive iterations set the controls such that the desired flight path is followed. The procedure is to move the control-motion pair in question to null the difference between the current calculated value and the desired final value. Table 3-14 in Volume III shows the control or variable to motion pairing used in REXOR. TRIM does not compute the motion of the entire rotorcraft, but only computes the motion of the rotor assembly (see Table 1-7). Other than accelerations, the remaining displacements and velocities are computed by a set of static relationships. This procedure saves time by constraining the flight track of the rotorcraft during TRIM, and eliminates what would otherwise might be a lengthy chasing procedure.

TRIM is called by MAIN. It performs executive functions, tabulates, plots, specifies motions of degrees of freedom inoperative in trim, and performs the trim algorithms until one of the trim tests is met and TRIM exits. There are no multiple entries. The normal trim is with the degrees of freedom operating for all the blades. The subroutine includes fast trim procedures using one blade only. These trim procedures are not supported.

The program initializes the new case down to label 9677. At this point the trim loop begins. The first calculations in the trim loop relate to updating for the next time point and are skipped by going to label 104 the first time into the trim loop at time zero. Figure 1-1 illustrates the entire sequence of operations in TRIM and shows the initial entry from MAIN.

Beginning with label 104, the program specifies the degrees of freedom inoperative during trim. These degrees of freedom are given in Table 1-7. The equations defining these degrees of freedom are taken directly from Volume I, or are derived from the same assumptions. Note that in TRIM the fuselage velocities and angles are the prime quantities rather than the principal axis values. This scheme is used to make the trimming quantities closely identifiable with normally measured quantities. Hub air velocities may be expressed in terms of fuselage data by inverting the equations of Volume I, Section 5.5.2:

TABLE 1-7. SPECIFICATIONS FOR DEGREES OF FREEDOM INOPERATIVE DURING TRIM

Displacement		Velocity		Acceleration	
Sym.	Equation	Sym.	Equation	Sym.	Equation
$\phi_{SP} = Y(17)$	$\left.\begin{matrix} \\ \\ \end{matrix}\right\} = \frac{1}{(d/e)}\left[T_{\psi_{PHn}}\right]^T \begin{Bmatrix} A_{1S} \\ B_{1S} \end{Bmatrix}$	$\dot{\phi}_{SP} = YD(17)$	$= 0.0$	$\ddot{\phi}_{SP} = YDD(17)$	$\left.\begin{matrix} \\ \\ \end{matrix}\right\} = \left[M^{-1}\right]\{F\}$
$\theta_{SP} = Y(18)$		$\dot{\theta}_{SP} = YD(18)$	$= 0.0$	$\ddot{\theta}_{SP} = YDD(18)$	
$Z_{SP} = Y(19)$	Trim Variable	$\dot{Z}_{SP} = YD(19)$	$= 0.0$	$\ddot{Z}_{SP} = YDD(19)$	
$\psi_R = Y(20)$	$= \dot{\psi}_R\, t$	$\dot{\psi}_R = YD(20)$	Input Quantity	$\ddot{\psi}_R = YDD(20)$	$= 0.0$
X_E	N/A	$u_H = Y(21)$	$\left.\begin{matrix} \\ \\ \end{matrix}\right\} = f\,(u_H, v_H, w_H, p_H, q_H, r_H, \phi_S, \theta_S)$	$\ddot{X}_H^{\,I} = YDD(21)$	$\left.\begin{matrix} \\ \\ \end{matrix}\right\} = -\begin{bmatrix} 0 & r & -q \\ -r & 0 & p \\ q & -p & 0 \end{bmatrix}_H \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_H - \left[T_{E-H}\right]\begin{Bmatrix} 0 \\ 0 \\ 32.2 \end{Bmatrix}$
Y_E	N/A	$v_H = Y(22)$		$\ddot{Y}_H^{\,I} = YDD(22)$	
Z_E	Input Quantity	$w_H = Y(23)$		$\ddot{Z}_H^{\,I} = YDD(23)$	
$\phi_E = Y(27)$	Initialized as $Tan^{-1}\,(\delta_X/32.2)$ 1	$r_H = Y(24)$	$\dot{\psi}_E \sin\theta_E = \frac{\delta_X}{V_T} \sin\theta_E$	$\dot{p}_H = YD(24),\ YDD(24)$	$= 0.0$
$\theta_E = Y(28)$	$= f\,(\alpha_H, \beta_H, \phi_E, \gamma_H)$	$q_H = Y(25)$	$= \dot{\psi}_E \cos\theta_E \sin\phi_E$	$\dot{q}_H = YD(25),\ YDD(25)$	$= 0.0$
$\psi_E = Y(29)$	$= 0.0$	$r_H = Y(26)$	$= \dot{\psi}_E \cos\theta_E \cos\phi_E$	$\dot{r}_H = YD(26),\ YDD(26)$	$= 0.0$
$\phi_S = Z(3)$	Trim Variable	$\dot{\phi}_S = ZD(3)$	$= 0.0$	$\ddot{\phi}_S = YDD(27),\ ZDD(3)$	$= 0.0$
$\theta_S = Z(4)$	Trim Variable	$\dot{\theta}_S = ZD(3)$	$= 0.0$	$\ddot{\theta}_S = YDD(28),\ ZDD(4)$	$= 0.0$

1 $\delta_X = TURNSN \sqrt{TURNLF * TURNLF - 1}$ where TURNSN and TURNLF are inputs

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_H^I = \left[T_{H-F}\right]^T \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_F^I - \begin{Bmatrix} \dot{\theta}_S \ \partial X_F/\partial\theta_S \\ \dot{\phi}_S \ \partial Y_F/\partial\phi_S \\ 0 \end{Bmatrix} - \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{Bmatrix} \theta_S \ \partial X_F/\partial\theta_S \\ \phi_S \ \partial Y_F/\partial\phi_S \\ 0 \end{Bmatrix} \quad (1\text{-}84)$$

where

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_F^I = \begin{Bmatrix} V_T \ \sqrt{1 - \sin^2 \beta_F} \cos \alpha_F \\ V_T \sin \beta_F \\ V_T \ \sqrt{1 - \sin^2 \beta_F} \sin \alpha_F \end{Bmatrix} \quad (1\text{-}85)$$

The quantities V_T (VT), α_F (ALPHA) and β_F (BET) are inputs or trim variables.

The remaining item is the pitch attitude, θ_E. This quantity is derived as an explicit calculation rather than the looping shown in Volume I, Section 5.5.1 for FLY.

Starting with the identity,

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_H^I = \left[T_{E-H}\right] \begin{Bmatrix} V_T \cos \gamma_H \\ 0 \\ -V_T \sin \gamma_H \end{Bmatrix} = \left[T_{\alpha_H}\right]\left[T_{\beta_H}\right] \begin{Bmatrix} V_T \\ 0 \\ 0 \end{Bmatrix} \quad (1\text{-}86)$$

where

$$\left[T_{\alpha_H}\right] = \begin{bmatrix} \cos \alpha_H & 0 & -\sin \alpha_H \\ 0 & 1 & 0 \\ \sin \alpha_H & 0 & \cos \alpha_H \end{bmatrix} \quad (1\text{-}87)$$

and

$$\left[T_{\beta_H}\right] = \begin{bmatrix} \cos\beta_H & \sin\beta_H & 0 \\ -\sin\beta_H & \cos\beta_H & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1-88}$$

The identity can be expanded and solved for θ_E. This gives:

$$\theta_E = \sin^{-1}\left[\left\{\sin\gamma_H \cos\beta_H \cos\alpha_H + A\sqrt{\cos^2\alpha_H \cos^2\beta_H + A^2 - \sin^2\alpha_F}\right\} \Big/ \left(\cos^2\alpha_H \cos^2\beta_H + A^2\right)\right] \tag{1-89}$$

where

$$A = \sin\beta_H \sin\phi_E + \sin\alpha_H \cos\beta_H \cos\phi_E \tag{1-90}$$

From Volume I, Figure 5-2 but for hub axis:

$$\alpha_H = w_H \Big/ \sqrt{u_H^{\,2} + w_H^{\,2}} \tag{1-91}$$

$$\beta_H = v_H/V_T \tag{1-92}$$

The climb angle γ_H (GAMMA) is an input or a trim variable.

The program modifies the specifications slightly if FLY is conducted with the shaft fixed simulating a wind tunnel model with rigid support or if the pitch and roll rates are specified by inputs. Almost all the specifications are complete by about label 112.

Once the trim motions are specified, the program proceeds to call a large number of subroutines and their entries: DERIV, DERIVF, LOADS, ACCEL,

CORECT, BMOVE, and ABIRD. Note that if harmonic analysis is being conducted, DERIV, DERIVF and SWEEP are called again so the blade loads can be recomputed (and made timewise correct) using the accelerations updated in ACCEL before integrating for the velocities and displacements. These calls, along with some fast trim programming, occupy the program to just beyond label 1045.

The remaining elements partially within the blade radial summation loop (ends at label 399) are the blade loads harmonic analysis (HSAVE) and associated terms.

The routine ends with the tension torsion pack elements and blade feathering torque, TMA. The blade loop ends at label 503.

The program next prepares output for harmonic analysis down to label 1053, for time histories down to label 107, and for TRIM start and finish tabulations down to label 109.

The variable FH is filled for the harmonic analysis parameters and PDATA is filled for the time-history parameters. The PDATA being collected is either for the normal time histories being plotted during the trim process or for the time histories of some of the parameters being harmonically analyzed. (Extra revolutions are added to trim if the harmonic analysis flag is on.) The definitions of some key variables are: TIMET, the elapsed time in trim; PTIME, the plot time same as TIMET until 500 plot points are collected; NPTS, the number of plot points collected; NPLTF, the number of time points skipped to the next plot point; and IPTS, a time point counter between plot points. SCALE and TSCLE are the rotor revolutions and seconds per inch of plot paper. CYCLE is the number of revolutions from the beginning of trim, and AZIMUTH is the number of time points from zero azimuth.

After some fast trim code from label 109 to 1081, the program conducts some end of trim tests. The first test is simply to determine if CYCLE equals TCUT, the total number of cycles the progr m is allowed to trim, an input. All the other tests are based on the trim variable size. The trim completion tests are done once per revolution, and permit TRIM to exit if the change in each and every control (CONTRL) from one time point to another is less than some small value built into the program. The trim bomb test causes control to exit TRIM if any of the monitored variables exceed a built-in value. This portion occupies the program until label 110., which also includes some additional fast trim code.

Next comes the prime pa t of TRIM where the trim variables are reevaluated. Volume III, Sections 3.3.2 and 3.3.3 are suggested reading The incremental change of the trim variable from one time point to the next is usually based on accelerations which are integrated and "filtered" by the FA variable. In effect, the high frequencies which contain the vibratory components are smoothed out by the integration process.

The filter also has bandpass characteristics, and as such only retains current and near current iteration values. Old trials are washed out. In general the trim variables then drive the integrated, filtered acceleration errors to zero. For the flexible shaft option, the shaft angles are determined from auxiliary equations giving the static deflection as a function of load. The static deflections thus determined are integrated and filtered for use in the main stream trim calculations.

The program at this point also readjusts the pilot stick and the control gyro positions once the swashplate trim is complete. All the above occupies the program down to label 117, which ends the TRIM loop.

Beyond the 117 label is programming which reverses the usual updating of old values of the motions of the primary degrees of freedom. The purpose here is to have the first time point in FLY the same as the last time point in TRIM. After label 1147 there is a short portion which updates and punches new trim cards, if so flagged, and calls RCPLOT. The calls for RCPLOT between labels 310 and 311 are for the harmonic analysis plots. The program ends by computing sine and cosine components as well as the magnitude and phase of certain rotor loads and the feather angle. This data is tabulated by the name XYZ.

1.3.31 TORS1

The isolated twist response of the blade at every station is determined in this subroutine. TORS1 initializes while entry TORS does the twist computing at every time point. FX, FY, and FZ are the blade shears integrated from the tip to the station in question. They equal the root values F(4,I), F(5,I), and F(6,I) minus the values from FSV saved in subroutine SWEEP during the integration proceeding from the root to the station in question. TORQUE, then, is torque at the shear center where XSV, YSV, and ZSV are the distance to the shear center in blade root axes as saved in SWEEP. DSOGJ is the reciprocal of the torsion stiffness, DTHG is the increment in twist angle over a blade section, and THTORS is the total twist from the tip to the given station. Only the displacement is computed. The twist velocity THTRD is taken as zero to help prevent numerical instabilities during dynamic stall on the retreating blade.

1.3.32 TRMPUN

TRMPUN punches those inputs which may vary during TRIM and describe the trim state of the model (Trim Save option). These variables include the trim control variables and the motions of the degrees of freedom. When these trim save cards are added to the input deck, the next case starts off where the old one ended. These cards can shorten the time to trim even if new, somewhat different, flight conditions are used.

Entry DSHIFT updates almost the same set of inputs as TRMPUN. The update is saved in RAS. As such DSHIFT might be useful during a single submittal of a number of similar runs where trim save card are not available.

DSHIFT and TRMPUN are called by TRIM if RA(2000) = TRMUPD or RA(47) = IPUNCH flag is on (=1).

1.3.33 XTERMO

This subprogram contains a major portion of the transformation matrices required in SWEEP. A given entry may use up to three angles. Multiple Euler rotations as well as derivatives are coded. Individual call descriptions are referred to the description in SWEEP. The coding of this subprogram has been machine produced by the IBM FORMAC procedure.

1.3.34 XTRP1, XTRP2, XTRP3

This is a set of special linear interpolation routines designed for speed. The interpolation technique does not require the classic table search to find the data of interest. These routines do require that the tabulated function be evaluated at constant argument intervals.

Algorithm - If x_0 is the first argument value and the data is evaluated at Δx intervals, then the location within the table of bracketing function values for a value of the argument x is η where

$$\eta = \left[\frac{x - x_0}{\Delta x}\right] \tag{1-93}$$

The brackets indicate the largest integer whose magnitude does not exceed the magnitude of $(x - x_0)/\Delta x$. The interpolating formula, based on the point-slope formula, is given as

$$y = y_n + dx(y_{n+1} - y_n) \tag{1-94}$$

where

$$dx = \frac{x - x_0}{\Delta x} - n \tag{1-95}$$

This is shown to be correct if

$$x - x_0 = \eta \cdot \Delta x + (x - x_n) \qquad (1\text{-}96)$$

is substituted in the equation for dx.

The quantities x_0 and Δx are stored with the table of function values. The function of each routine is

XTRP1	computes	$F = f(x)$
XTRP2	computes	$F = f(x,y)$
XTRP3	computes	$F = f(x,y,z)$

There is one general table format for all routines. The table, T, must contain the following:

T(1)	x_0
T(2)	number of x breakpoints - 1
T(3)	$1/\Delta x$
T(4)	y_0
T(5)	number of y breakpoints - 1
T(6)	$1/\Delta y$
T(7)	z_0
T(8)	number of z breakpoints - 1
T(9)	$1/\Delta z$
T(10),...	table data on increasing x, then y, and then z.

1.3.35 XTRP

XTRP is a generalized table driven interpolation routine capable of evaluating functions of 1, 2, or 3 variables, either linearly or quadratically. The use of XTRP is thoroughly explained with comment cards associated with the module.

1.3.36 XTRP4 and XTRPCA

Together, these routines compute main rotor blade aerodynamic coefficients C_L and C_D where

$$C_L = C_L(M, \alpha, C_{L_i}, t/c) \tag{1-97}$$

$$C_D = C_D(M, \alpha, C_{L_i}, t/c) \tag{1-98}$$

These functions are defined over the ranges:

$$0 \leq \alpha \leq 360$$

$$0.1 \leq M \leq .9$$

$$0 \leq C_{L_i} \leq .69$$

$$0.06 \leq t/c \leq .12$$

by a series of tables. The functions are evaluated by linear interpolation methods with the use of XTRP. All associated data tables are built into the software via block data subprograms.

2. COMMON/SUBROUTINE DIRECTORY

The collection of subprograms which constitute REXOR contain many cross-referenced COMMON blocks and subroutines. Table 2-1 is presented as an aid to developing the source and usage of any particular item. The vertical listing on this table gives all the routines, and names or unnamed (one) COMMON blocks used in REXOR. A second column, headed by 'T' gives the use of the entry. The coding used is 'M' for main program, 'S' for subroutine, 'E' for entry of a subroutine, 'C' for common block. The list of names is in alphabetical order and numbered. The alphabetizing is by main to subroutines with a subalphabetizing of entry points under each subroutine. The COMMON blocks are listed last except for subroutines not included in the source deck. These subroutines are usually part of the computer operating (precompiled) package, and not particularly associated with REXOR. The numbering is repeated horizontally, and corresponds to the vertical name list.

The vertical list on the left-hand side is the calling or active routine or element, and the horizontal line lists the routines called or referenced. Numbers at grid intersections show there is a reference and the level of reference. One indicates a direct reference. Two or three show there is one or two intermediate references, respectively. Note that a subroutine name will show all the references to all the entry points bounded by that name. By elimination, the references associated with the subroutine name up to the point of the first entry name can be determined.

TABLE 2-1. COMMON SUBROUTINE DIRECTORY

NO	ROUTINE	T	1 12345 67890	11111 11112 12345 67890	22222 22223 12345 67890	33333 33334 12345 67890	44444 44445 12345 67890	55555 55556 12345 67890	66666 66667 12345 67890	77777 77778 12345 67890	88888 88889 12345 67890	99999 9999A 12345 67890	AAAAA AAAAB 12345 67890	BBBBB BBBBC 12345 67890	CCCCC CCCCD 12345 67890	DDDDD DDDD 12345 6789
1	MAIN	M	1221 22221	22222 22221	21222 21221	21222 12222	22121 21212	22222 22222	22222 22222	21111 11111	22222 22222	22222 22222	22222 22223	33333 33333	33333 33333	33333 3333
2	ACCEL1	S		1		1 1				111 1	11111					
3	ACCEL	E		1		1 1				111 1	11111					
4	AERO	S							111		11111	1				
5	BIRD1	S								111 1	1 1	11				
6	PBIRD	E								111 1	1 1	11				
7	ABIRD	E								111 1	1 1	11				
8	BBIAD	E								111 1	1 1	11				
9	COR	E								111 1	1 1	11				
10	BMOVE	S								1 1 1	1					
11	BSCALE	S														
12	CALOOK	S							1			11 1	2	2		
13	CNTRUL	S				1				1 1	1	1				
14	APCNTL	E				1				1 1	1	1				
15	PICNTL	E				1				1 1	1	1				
16	COULOM	S														
17	DERIV	S								111	1					
18	DERIVP	E								111	1					
19	DMASH	S								1 1						
20	ETORQ1	S								1 1						
21	ETORQ	E								1 1						
22	FLY	S	12 21211	22111 2111	1 1 11	1 2 2 121	1 2 2 1	2222 22222	22222 22222	21111 111	11112 22222	22122 21122	2 22 22 23	32222 22222	22222 22222	22222 2222
23	HARM1	S								1		1				
24	HARM	E								1		1				
25	HARM2	E								1		1				
26	IGYRO	S	1 11							121 2	2 2	22				
27	INTG	S								1 1	1					
28	PRED	E								1 1	1					
29	CORLCT	E								1 1	1					
30	LOADS1	S	2	2 4			2 1	2222 22222	22222 22212	21 1 12	12 22222	22 22 2 211	1 22	32222 22222	22222 22222	22222 2222
31	LOADS	E	2	2 2			2 1	2222 22222	22222 22212	21 1 12	12 22222	22 22 2 211	1 23	32222 22222	22222 22222	22222 2222
32	LSTUAT	S														
33	MIC26	S														
34	MINVR	S														
35	MPRNT	S									1					
36	PDATE	S											11			
37	PHORN	E								1 1 1						
38	PILOTA	S								1						
39	PILOT1	E								1						
40	PRINT1	S								1						
41	PRINT	E								1						
42	RCPLOT	S		1						11 1			11 11			
43	READIN	S				1	1			1			1			
44	STALL	S	1						222	1	22222	2				
45	SWEEP1	S	1	1 1			1	1111 11111	11111 22222	11 1 11	1 22222	21 22 2 1	13	32222 22222	22222 22222	22222 2222
46	SWEEP	E	1	1 1			1	1111 11111	11111 22222	11 1 11	1 22222	21 22 2 1	13	32222 22222	22222 22222	22222 2222
47	TORS1	S								1 1 1			1			
48	TORS	E								1 1 1			1			
49	TRIM	S	13 11 1	23 2111	111 11	1 212 1	1 3 1 1 1	13333 33333	33333 33323	31111 111	11112 33333	32133 3 112	2 22 22 34	42222 22222	22222 22222	22222 2222
50	TRNPUN	S								1						
51	DSHIFT	E								1						
52	XTERM0	S														
53	XTERM1	E														
54	XTERM2	E														
55	XTERM3	E														
56	XTERM4	E														
57	XTERM5	E														
58	XTERM6	E														
59	XTERM7	E														
60	XTERM8	E														
61	XTERMV	E														
62	XTERMA	E														
63	XTERMC	E														
64	XTERMD	E														
65	XTERME	E														
66	XFPP	S											1	1		
67	XTAPCA	S							1				2	21111 11111	11111 11111	11111 1111
68	XTAP1	S														
69	XTAP2	S														
70	XTAP3	S														

TABLE _-1. COMMON SUBROUTINE DIRECTORY - Continued

NO	ROUTINE	T	1 12345 67890	11111 11112 12345 67890	22222 22223 12345 67890	33333 33334 12345 67890	44444 44445 12345 67890	55555 55556 12345 67890	66666 66667 12345 67890	77777 77778 12345 67890	88888 88889 12345 67890	99999 9999A 12345 67890	AAAAA AAAAB 12345 67890	BBBBB BBBBC 12345 67890	CCCCC CCCCD 12345 67890	DDDDD DDDD 12345 6789
[illegible]	[illegible]	[illegible]											3	32222 22222	22222 22222	22222 2222
72		C														
73	[illegible]	C														
74	INPUT	C														
75	[illegible]	C														
76	[illegible]	C														
77	MNSWLD	C														
78	MBLADE	C														
79	RERLAD	S														
80	PLLTS	[illegible]														
81	START	C														
82	FUSE	C														
83	MNSWAC	C														
84	ACCHN	C														
85	TNJPP	C														
86	CHA	C														
87	CHAM	C														
88	CLAT	C														
89	CLATH	C														
90	COAT	C														
91	CCATH	C														
92	[illegible]	C														
93	MMWRD	C														
94	CMT1CH	C														
95	CMT2CH	C														
96	CT1SCH	C														
97	TRFLCH	C														
98	MSH	C														
99	LUM	C														
100	PROG1	C														
101	PROG2	C														
102	TDATE	S														
103	MOVE	S														
104	PLOT	S														
105	SYMBOL	S														
106	NUMBER	S														
107	LINE	S														
108	TRMLNC	S														
109	TOR	C														
110	TABLID	C														
111	EXIT	S														
112	CMT1CL	C														
113	CMT1CD	C														
114	CMT2CL	C														
115	CMT2CD	C														
116	CMT3CL	C														
117	CMT3CD	C														
118	CMT4CL	C														
119	CMT4CD	C														
120	CMT5CL	C														
121	CMT5CD	C														
122	CMT6CL	C														
123	CMT6CD	C														
124	CMT7CL	C														
125	CMT7CD	C														
126	CT1SCL	C														
127	CT1SCD	C														
128	CT2SCL	C														
129	[illegible]	C														
130	[illegible]	C														
131	CT3SCD	C														
132	CT4SCL	C														
133	[illegible]	C														
134	[illegible]	C														
135	CT5S	C														
136	CT6SCL	C														
137	CT6SCD	C														
138	CT7SCL	C														
139	CT7SCD	C														

3. TIME AND SPATIAL INTEGRATION

The equations of Volume I have treated the flying vehicle to be composed mostly of a number of rigid body elements. For the blade, however, convenience dictates an integration process with distributed mass and inertial data. The subroutine SWEEP ends with a trapezoidal integration of all blade generalized masses and loads. This algorithm approximates th integral from root to a station X.

$$F(X) = \int_0^X F' \, dX \tag{2-1}$$

by

$$F(n_X) = \sum_{i=1}^{n_X} \frac{[F'(i) + F'(i+1)]\ [X(i+1) - X(i)]}{2} \tag{2-2}$$

The more complex Simpson rule is frequently used, but trapezoidal integration is more convenient because of its ready geometric interpretation, and is especially useful for applying aerodynamic 'tip loss'.

The time integration of the degrees of freedom starts with a Euler integration which simulates

$$P(t) = \int_0^t \dot{P} \, dt + P(0) \tag{2-3}$$

as

$$P(n_t) = \sum_{j=1}^{n_t} \dot{P}(j) \, \Delta t + P(0) \tag{2-4}$$

Δt being a constant interval between time points. After four time points are computed, and enough old data collected, a switch is made to Adams-Bashforth integration.

$$P(n_T) = \sum_{j=1}^{n_T} \left[55\dot{P}(j) - 59\dot{P}(j-1) + 37\dot{P}(j-2) - 9\dot{P}(j-3)\right] \frac{\Delta t}{24} + P(0) \tag{2-5}$$

This sequence is used in INTG for the majority of the degrees of freedom, and in BIRD1 for gyro and shaft bending motions.

Note that the operation of the integration scheme can severely affect the apparent mode damping. This is important to the inplane mode which characteristically has low damping. The question as to whether the mode is stable or unstable is of extreme interest. For example, suppose computations are 180 points per revolution, or two degree azimuth in FLY. This suggests that the phase of a parameter oscillating at one per revolution (1P) is limited to an ultimate resolution of two degrees; at 2P, ultimate resolution is four degrees, etc. For a second-order system undergoing transient response

$$\ddot{x} + g\omega_0\dot{x} + \omega_0^2 x = f \tag{2-6}$$

the ratio of the magnitude of the damping term to either the spring or mass term for an oscillation at the natural frequency ω_0 is g. In the example at 1P, g would be limited in precision to about 0.01 (= 2 deg). This level is roughly the order of structural damping. The analysis of a large number of oscillations might give greater precision; however, the above position is conservative. The foregoing argument assumes the model has all the physical components of importance described and a sufficient number of blade mass elements.

4. AERO LOOKUP - MAIN ROTOR

The sequence of main rotor blade section aerodynamics computations is explained in Volume I Sections 7.2.2 through 7.2.4. The computer code corresponding to these procedures is explained in this section.

All of these computations are initiated through the routine SWEEP. Depending on the selection of ILOOK = RA(2689), either the direct aero tables (seven table lookup) or tailored to specific geometry tables (fast aero) are used. Note that these tables can be replaced by user supplied aerodynamic data so long as the CALL arguments coincide.

4.1 BASE SET OF AIRFOILS, CAMBER AND THICKNESS RATIO

The seven table lookup, Table 4-1 is a grouping of the available table set, Table 4-2, according to thickness ratio and design lift coefficient. SWEEP accesses the C_L, C_D part of this data for ILOOK = 1 via the interpolation routine XTRP4. XTRP4 logic determines the proper design lift coefficient and thickness tables to bracket the desired values through the routine XTRPCA, and performs the interpolation. The data is sorted and retrieved by the COMMON naming, Table 4-2.

The C_M value required is determined through the routine CMLOOK. No interpolation to design C_L or thickness ratio is made. Rather, the input IFOIL = RA(2690) selects 0012 airfoil (=0) or 23012 (=1).

4.2 REDUCTION TO SMALLER TABLE SETS

The seven table data (plus C_M tables) may be collapsed to a set directly keyed to the geometry at hand. The scheme used in REXOR uses equally spaced data index points, which leads to rapid access. This procedure, called Fast Aero, is called from SWEEP for ILOOK = 0. SWEEP uses the Fast Aero tables through the routine AERO. This routine is also used by STALL (dynamic stall) which is called by SWEEP for ISTALL = RA(2555) = 0.

The C_L and C_D data for Fast Aero is grouped according to normal angle of attack range (± 30 degrees) with Mach effects and the remaining angle distribution treated as incompressible flow. The Fast Aero example is shown in Figure 4-1, and is constructed and referenced by thickness ratio for the AH-56A blade. This data is referenced for ± 30 degrees by a trivariant interpolation in the routine XTRP3 which is called by AERO. The trivariant interpolation is explained in Volume I Section 7.2.4. For the incompressible flow range a bivariant interpolation, called as routine XTRP2, is used.

TABLE 4-1. SEVEN TABLE LOOKUP			
Table Grouping	Included Tables	Design CL	Thickness
1	CMT1CL CMT1CD CT3SCL CT3SCD	0	0.12
2	CMT2CL CMT2CD CT2SCL CT2SCD	0	0.09
3	CMT3CL CMT3CD CT1SCL CT1SCD	0	0.06
4	CMT4CL CMT4CD CT4SCL CT4SCD	0.09	0.06
5	CMT5CL CMT5CD CT5SCL CT5SCD	0.39	0.09
6	CMT6CL CMT6CD CT6SCL CT6SCD	0.35	0.12
7	CMT7CL CMT7CD CT7SCL CT7SCD	0.69	0.12

TABLE 4-2. BASE AIRFOIL DATA

Table	Common Name	Camber	Thickness	Design CL	α Range	Mach Range	Output	NACA Type
1	CMT1CL	0	0.12	0	±30	(1)	CL	(0)3012
	CMT1CD	0	0.12	0	±30	(4)	CD	(0)3012
2	CMT2CL	0	0.09	0	±30	(2)	CL	(0)3009
	CMT2CD	0	0.09	0	±30	(3)	CD	(0)3009
3	CMT3CL	0	0.06	0	±30	(5)	CL	(0)3006
	CMT3CD	0	0.06	0	±30	(6)	CD	(0)3006
4	CMT4CL	0.6	0.06	0.09	±30	(5)	CL	(0.6)3006
	CMT4CD	0.6	0.06	0.09	±30	(6)	CD	(0.6)3006
5	CMT5CL	2.6	0.09	0.39	±30	(7)	CL	(2.6)3009
	CMT5CD	2.6	0.09	0.39	± 30	(8)	CD	(2.6)3009
6	CMT6CL	2.3	0.12	0.35	±30	(7)	CL	(2.3)3012
	CMT6CD	2.3	0.12	0.35	±30	(9)	CD	(2.3)3012
7	CMT7CL	4.6	0.12	0.69	±30	(7)	CL	(4.6)3012
	CMT7CD	4.6	0.12	0.69	±30	(9)	CD	(4.6)3012
8	CT1SCL	0	0.06	0	+30 +330	INCOMP	CL	(0)3006
	CT1SCD	0	0.06	0	+30 +330	INCOMP	CD	(0)3006
	CT2SCL	0	0.09	0	+30 +330	INCOMP	CL	(0)3009
	CT2SCD	0	0.09	0	+30 +330	INCOMP	CD	(0)3009
	CT3SCL	0	0.12	0	+30 +330	INCOMP	CL	(0)3012
	CT3SCD	0	0.12	0	+30 +330	INCOMP	CD	(0)3012
9	CT4SCL	0.6	0.06	0.09	+30 +330	INCOMP	CL	(0.6)3006
	CT4SCD	0.6	0.06	0.09	+30 +330	INCOMP	CD	(0.6)3006

TABLE 4-2 - Continued

Table	Common Name	Camber	Thickness	Design CL	α Range	Mach Range	Output	NACA Type
9	CT5SCL	2.6	0.06	0.39	+30 +330	INCOMP	CL	(2.6)3006
	CT5SCD	2.6	0.06	0.39	+30 +330	INCOMP	CD	(2.6)3006
	CT6SCL	2.3	0.12	0.35	+30 +330	INCOMP	CL	(2.3)3012
	CT6SCD	2.3	0.12	0.35	+30 +330	INCOMP	CD	(2.3)3012
	CT7SCL	4.6	0.12	0.69	+30 +330	INCOMP	CL	(4.6)3012
	CT7SCD	4.6	0.12	0.69	+30 +330	INCOMP	CD	(4.6)3012
10	CMT1CM	2	0.08	0.3	±30	(10)	CM	23008
	CT1SCM*	0	0.12	0.0	+30 +330	INCOMP	CM	(0)3012
11	CMT2CM	0	0.12	0.0	±30	(11)	CM	(0)3012
	CT1SCM*	0	0.12	0.0	+30 +330	INCOMP	CM	(0)3012

*REPEATED

Mach Ranges

(1) 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.85, 1.0

(2) 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.55, 0.6, 0.65, 0.7, 0.757, 0.85, 1.0

(3) 0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.915, 1

(4) 0, 0.738, 0.78, 0.805, 0.85, 0.9

(5) 0, 0.2, 0.4, 0.5, 0.6, 0.65, 0.7, 0.75, 0.805, 0.85, 1

(6) 0, 0.4, 0.5, 0.6, 0.7, 0.75, 0.8, 0.85, 0.9, 0.935, .

TABLE 4-2 - Concluded	
Mach Ranges	
(7)	0, 0.2, 0.3, 0.4, 0.5, 0.55, 0.6, 0.65, 0.7, 0.757, 0.85, 1.0
(8)	0, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.85, 0.915, 1
(9)	0, 0.2, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
(10)	0, 0.3, 0.4, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.875, 0.925, 1
(11)	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.9

Due to the limited section data available, the C_M data is not displayed as a function of thickness ratio in Fast Aero, but is bivariantly interpolated for ±30 degrees and univariantly interpolated for incompressible flow, XTRP1. The base data is for a design lift coefficient of 0.3 and thickness ratio of 0.08 (NACA 23008). The compressible flow range part of this data is curve shifted on the angle of attack axis to account for other thickness ratios as shown in Figure 4-2. This operation is performed in AERO.

4.3 RANGE OF ENTRIES

The existing Fast Aero set is specifically constructed for the AH-56A blade. However, the seven table set contains a large spectrum of sections made by drooping the nose portion of symmetrical four digit foils. These are known as the five digit series and the equivalent designation is given on Table 4-2. Therefore a Fast Aero set could be constructed for any blade composed of five-digit airfoil sections.

4.4 DATA CORRECTIONS

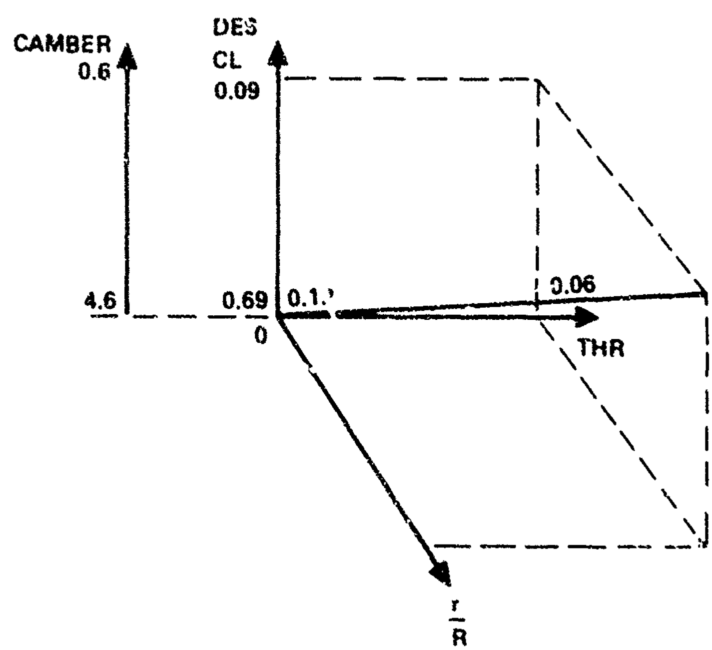
A C_M trim is provided in AERO in the compressible flow range for ICMBL (IBLADE, RA 1300) = 3 by the coefficient DCMR1.

A second C_M trim is available in SWEEP to account for blade trim tab. This trim quantity DCMR operates between blade stations KTO and KT1.

An override of C_L = 0, C_M = 0 is set in SWEEP for the blade root cutout. The C_D value calculated is used as calculated from the tables.

TABLE	COMMON NAME	OUTPUT	ANGLE OF ATTACK MIN	MAX	Δ	THICKNESS RATIO MIN	MAX	Δ	MACH MIN	MAX	Δ
1	CLATM	CL	-30.6	33.4	1.0	0.06	0.12	0.03	0	0.9	0.05
2	CLAT	CL	33.38	330.37	0.5	0.06	0.12	0.03	0	0	1
3	CDATM	CD	-30.6	33.4	1.0	0.06	0.12	0.03	0	0.9	0.05
4	CDAT	CD	33.38	330.37	0.5	0.06	0.12	0.03	0	0	1
5	CMAM	CM	-30	30	0.5	N/A	N/A	N/A	0.3	0.9	0.025
6	CMA	CM	30	330	0.5	N/A	N/A	N/A	0	0	1

NOTE 1: FOR CL, CD DATA ACCESSION IS BY MEANS OF THICKNESS RATIO AS THR, DESIGN CL AND BLADE STATION ARE LINEARLY RELATED



NOTE 2: CM DATA IS TABULATED TO ANGLE OF ATTACK AND MACH (OPT) ONLY. DATA IS CURVE SHIFTED FOR THICKNESS RATIO (I.E., STATION) FUNCTION

Figure 4-1. Fast Aero Tables.

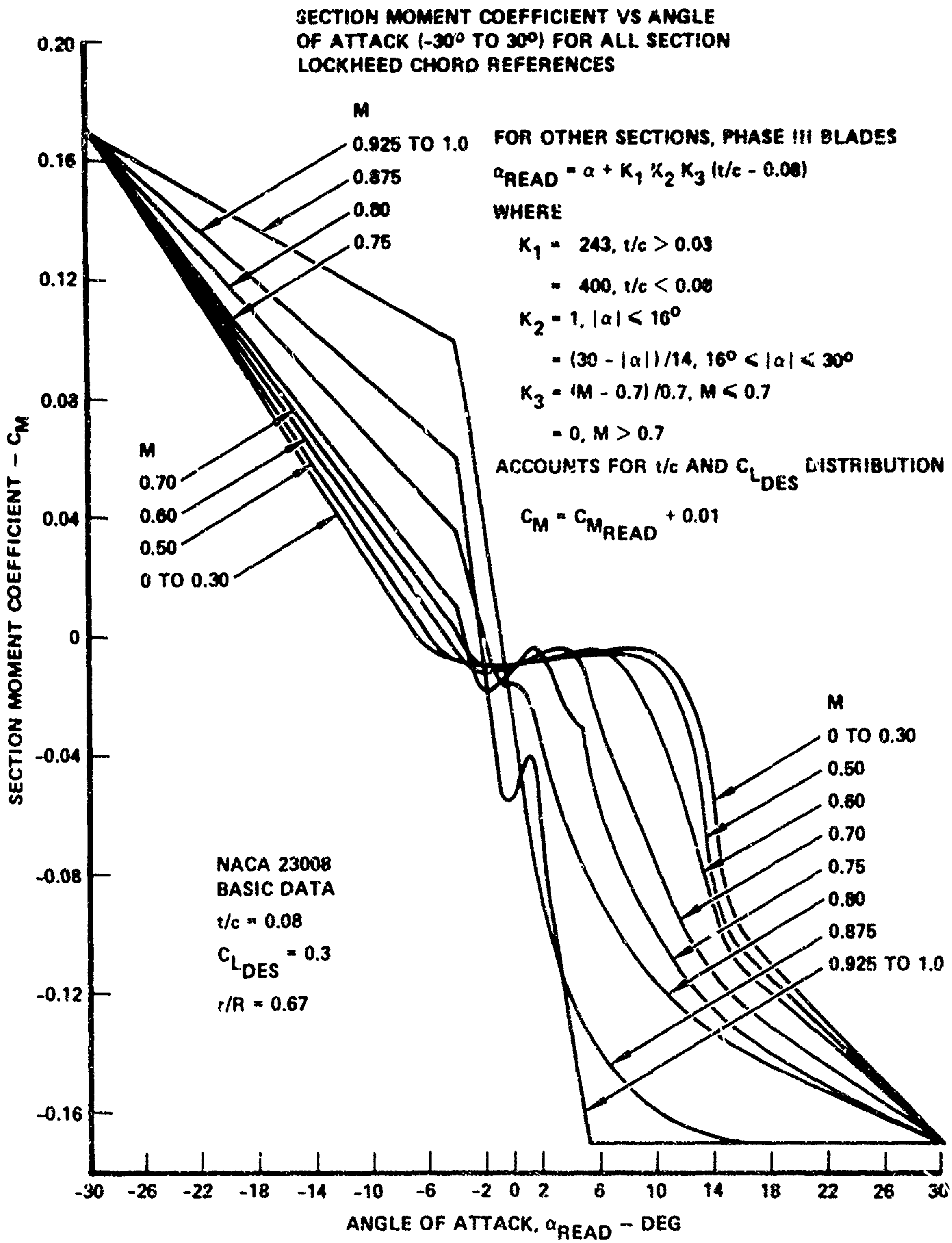


Figure 4-2. Fast Aero C_M Calculations.

5. COMPLETE SOURCE LISTING

Due to the large number of pages in the REXOR program source listing, this material is handled under a separate binder. Copies may be obtained from the distributing agency, USAAMRDL, Eustis Directorate, Ft. Eustis, Virginia.

LIST OF SYMBOLS

SYMBOLS

a	arbitrary vector
$\ddot{a}_0$	acceleration vector, ft/sec^2
a_1	longitudinal component of blade first harmonic flapping, rad
$[A]$	generalized mass element matrix
$A_{1,2,3}$	modal variables
A_{1n}	generalized displacement of nth blade, first mode
A_{2n}	generalized displacement of nth blade, second mode
A_{3n}	generalized displacement of nth blade, third mode
A_{1S}	cosine component of blade first harmonic cyclic, rad
b	number of main rotor blades; arbitrary vector
D	dissipation function
B_{1S}	sine component of blade first harmonic cyclic, rad
c	blade segment chord, ft
$[C]$	damping matrix
C_D	aerodynamic drag coefficient
C_L	aerodynamic lift coefficient
C_M	aerodynamic pitching moment coefficient
C_P	power coefficient
C_T	thrust coefficient

$C_{X,Y,Z}$	linear damping, lb/ft/sec
$C_{\phi,\theta,\psi}$	rotary damping, ft-lb/rad/sec
$C_{1,2,3}$	blade bending to feathering couplings
$C(k)$	lift deficiency function
d	infinitesimal increment
dr	increment in rotor, radius, ft
dt	increment in time, sec
d/dt	derivative with respect to time
$(d/e)_0$	swashplate to feather gear ratio, zero collective
$(d/e)_1$	swashplate to feather gear ratio slope with collective
e	pitch horn effective crank arm, ft
EI	blade bending stiffness distribution, lb-ft^2
f_{iMR}	ground effect factor for main rotor
F	factor; force, lb
$F_{X,Y,Z}$	force components along X,Y,Z directions, lb
$F_{\phi,\theta,\psi}$	generalized force about ϕ, θ, ψ axis
$F_{\beta PH}$	feathering mode generalized force
g	gravity, ft/sec^2
$g_{X,Y,Z}$	gravity components along X,Y,Z directions
G	gear ratio
$\{G\}$	generalized force vector
$\ddot{G}$	gyro angular acceleration partial product
GJ	blade torsional stiffness, lb-ft^2
I_X	$= \Sigma m_i X_i^2$, slug-ft^2
I_Y	$= \Sigma m_i Y_i^2$, slug-ft^2

I_Z	$= \Sigma m_i Z_i^2$, slug-ft^2
I_{XX}	$= \Sigma m_i (Y_i^2 + Z_i^2)$, slug-ft^2
I_{YY}	$= \Sigma m_i (X_i^2 + Z_i^2)$, slug-ft^2
I_{ZZ}	$= \Sigma m_i (X_i^2 + Y_i^2)$, slug-ft^2
I_{XY}	$= \Sigma m_i X_i Y_i$, slug-ft^2
I_{XZ}	$= \Sigma m_i X_i Z_i$, slug-ft^2
I_{YZ}	$= \Sigma m_i Y_i Z_i$, slug-ft^2
i	unit vector
j	unit vector
J	advance ratio
k	number of blade radial stations; reduced frequency, rad/sec; unit vector
$[K]$	spring matrix
K_{mj}	blade spring matrix element
$K_{X,Y,Z}$	spring constants along X,Y,Z direction, lb/ft
$K_{\phi,\theta,\psi}$	spring rates about ϕ, θ, ψ axis, ft-lb/rad
l_{IB}	location inboard feather bearing, ft
l_{OB}	location outboard feather bearing, ft
l_p	radial location of intersection of precone and feather axis, ft
l_{TTI}	tension torsion pack length, ft
L	rolling moment, ft-lb
m	mass of element, slugs
m_F	summed fuselage coordinate mass, slugs
m_H	summed hub axis mass, slugs
m_i	mass of ith particle or blade segment, slugs

S	Laplace variable, path of motion of particle p
S_{NA}	blade spline length along neutral axis locii, ft
t	time
T	kinetic energy, ft-lb
$[T]$	transformation of coordinates matrix
T_{TT}	tension in tension - torsion pack, lb
u	velocity in X direction, ft/sec
U	potential energy function, ft-lb; strain energy, ft-lb
$U_{C,P,S,T}$	air velocity on blade element, ft/sec
v	velocity in Y direction, ft/sec
V_T	trajectory velocity
w	velocity in Z direction, ft/sec
w_{iMR}	main rotor collective inflow, ft/sec
w_{iTR}	tail rotor collective inflow, ft/sec
x	motion in X direction, ft; blade span location
X	coordinate direction; axis; deflection, ft; location, ft; cross product
X_{SW}	blade radial station of sweep and jog, ft
X_T	trajectory path, ft
X_{TR}	tail rotor longitudinal force, lb
y	motion in Y direction, ft
Y	coordinate direction; axis; deflection, ft; location, ft
$Y_{TTO_{1,2,3}}$	tension torsion pack outboard end modal coefficients
Y_{ONA}	difference between Y direction locations of cg and neutral axis points of blade element, ft

m_{SP}	swashplate summed mass, slugs
M	pitching moment, ft-lb; $= \Sigma m_i$, slugs
$[M]$	generalized mass matrix
M_{rk}	generalized mass matrix element
$M_{\bar{X}}$	$= \Sigma m_i X_i$, slug-ft
$M_{\bar{Y}}$	$= \Sigma m_i Y_i$, slug-ft
$M_{\bar{Z}}$	$= \Sigma m_i Z_i$, slug-ft
$M_{X,Y,Z}$	moments about X,Y,Z axis, ft-lb
M_{ϕ}	blade torsional moment, ft-lb/ft
N	number of system particles
p	angular velocity about X axis, rad/sec; particle
p_{iMR}	main rotor pitch moment inflow, ft/sec
q	generalized coordinate; angular velocity about Y axis, rad/sec
q_{iMR}	main rotor roll moment inflow, ft/sec
Q	generalized forcing function
Q_A	aerodynamic pressure times reference wing area, lb
QLOADS	total nonmain rotor aerodynamic loads matrix
Q_{TR}	tail rotor torque, ft-lb
r	general vector; radius of curvature, ft; angular velocity about Z axis, rad/sec; notation for (X,Y,Z)
r_S	static blade shape
R	vector displacement of particle p in X,Y,Z axis system
R_0	vector displacement of x,y,z origin in X,Y,Z system
$R_{Z\phi,Z\theta}$	gyro damper coupling ratios

z	motion in Z direction
Z	coordinate direction; axis; deflection, ft; location, ft
Z_{SP}	relative swashplate vertical displacement with respect to the hub, ft
$Z_{TTO_{1,2,3}}$	tension-torsion pack outboard end modal coefficients
Z_{OBL}	teetering rotor undersling, ft
Z_{OF}	hub set distance above fuselage set, ft
Z_{OSP}	hub set distance above swashplate set, ft
Z_{OTTI}	blade vertical offset at outboard end of tension - torsion pack, ft
α	angle of attack, rad
α_{Ω}	angle of attack with hub set, rad
β	sideslip angle, rad
β_{FA}	blade feathering angle, rad
β_{PHn}	feathering/pitch-horn bending or dynamic torsion generalized coordinate displacement
β_0	blade droop relative to precone angle, rad
γ	blade sweep angle, rad; dynamic stall delay, sec
γ_T	trajectory path angle with E set, rad
δ	limit deflection, rad; freeplay, rad; small increment
δ_{3TR}	tail rotor pitch - flap coupling
$\partial\varepsilon/\partial\alpha$	downwash factor of wing on horizontal tail
ζ	vector notation of ϕ, θ, ψ
θ	rotation about Y axis, rad
θ_0	collective blade angle, rad
Λ	sideslip at blade element, rad
ρ	air density, slugs/ft^3

τ	time constant, sec; natural period, sec
τ_0	feathering axis precone, rad
ϕ	rotation about X axis, rad
ϕ_F	feathering angle, rad
ϕ_{Fn}	feathering angle of blade element of nth blade, rad
ϕ_{REF}	blade root reference feather angle, rad
ϕ_T	blade torsion, rad
ϕ_T	sum of blade twist and torsion, rad
X_{iMR}	wake angle of main rotor, deg
ψ	rotation about Z axis, rad; sideslip angle with hub set, rad
ψ_c	control input axis rotation from swashplate, rad
ψ_{PH}	pitch lead angle, deg
ψ_T	trajectory path yaw with E set, rad
ψ_W	main rotor apparent airflow angle, rad
ω	rotational speed, rad/sec; angular velocity, rad/sec; natural frequency, rad/sec
∂	partial derivative, derivation

SUBSCRIPTS

a	arbitrary coordinate set a
A	due to aerodynamics
b	arbitrary coordinate set b
BEND	associated with blade elastic bending
BLE	blade element coordinate system
BLn	blade reference axis system for the nth blade

C	associated with pilot control input, chordwise
CG	associated with center of gravity location
CORR	corrective, correction
DW	referring to downwash
DYN	referring to dynamic component
E	earth axis
ENG	associated with powerplant - engine
EST	estimated
F	fuselage axis; associated with blade feathering
FA	referring to blade feather axis
FB	associated with feedback
Fn	associated with feathering of the nth blade
FR	due to friction
G	referring to gyro or gyro coordinate system
GEN	associated with gas generator section of powerplant
GFB	associated with gyro control feedback
GSP	gyro to swashplate connection
GUB	relating to gyro gimbal unbalance
H	referring to hub or principal reference axis system
HT	associated with horizontal tail
i	referring to inflow, particle
IB	referring to inboard feather bearing location
j	spring matrix index
jog	associated with blade attachment joggle
J	associated with gyro end of feedback rod linkage

Jn	associated with feedback rod coming from the nth blade
k	generalized mass index
LAG	associated with lead-lag damper
LIMIT	signifying limiting value
m	blade mode index, spring matrix index
MR	associated with main rotor
n	blade number index
NA	referring to blade segment neutral axis
NEW	newly determined value
NO	normal (to airflow) component
NR	pertaining to nonrotating value
OB	referring to outboard feather bearing location
OLD	value from previous time step
P	associated with propeller; perpendicular blade component
PH	referring to pitch horn
r	generalized mass index
R	referring to rotor axis system
REF	associated with blade feather reference value
RM	referring to control gyro feedback lever moment
S	referring to blade spanwise velocity; general mode; static; structural; shaft
SC	referring to blade segment shear center
SP	referring to swashplate
SP_c	command to swashplate
S, SP	referring to swashplate limit stop

STEADY	steady component
SW	referring to blade sweep angle location
T	associated with trajectory path relating to E axis; tangential blade component; blade torsion; blade twist
TR	associated with the tail rotor
TRIM	initial or trim value
TT	associated with tension torsion pack
TTI	referring to inboard end of tension torsion pack
TTO	referring to outboard end of tension torsion pack
TW	associated with blade twist (built in)
UB	relating to control gyro unbalance
UNSTEADY	associated with unsteady component
VT	associated with vertical tail
WING	associated with the wing
X	relating to component in X direction
Y	relating to component in Y direction
YA	relating to aerodynamic component in Y direction
Z	relating to component in Z direction
ZA	relating to aerodynamic component in Y direction
0	(nought) associated with collective value, coordinate axis value, with respect to principal reference axis, blade root summation
1,2,3	with respect to blade modes 1, 2, or 3
$\dot{1}S$	first harmonic component shaft axis feathering
1/4 c	with respect to blade 1/4 chord
3/4 c	with respect to blade 3/4 chord

β_{PHn}	associated with the feathering mode of the nth blade
ϕ	relating to component in the ϕ direction
θ	relating to component in the θ direction
ψ	relating to component in the ψ direction

SUPERSCRIPTS

i	referring to inertial reference
T	matrix transpose
$(\bar{\ })$	(bar) average quantity
$(\ ')$	(prime) slope with respect to blade span
$(\dot{\ })$	(dot) time derivative of basic quantity
$(\ddot{\ })$	(double dot) second time derivative
$(^{-1})$	matrix inverse
$(\vec{\ })$	vector quantity

POSTSCRIPTS

(i)	blade radial station index
(n)	blade number index